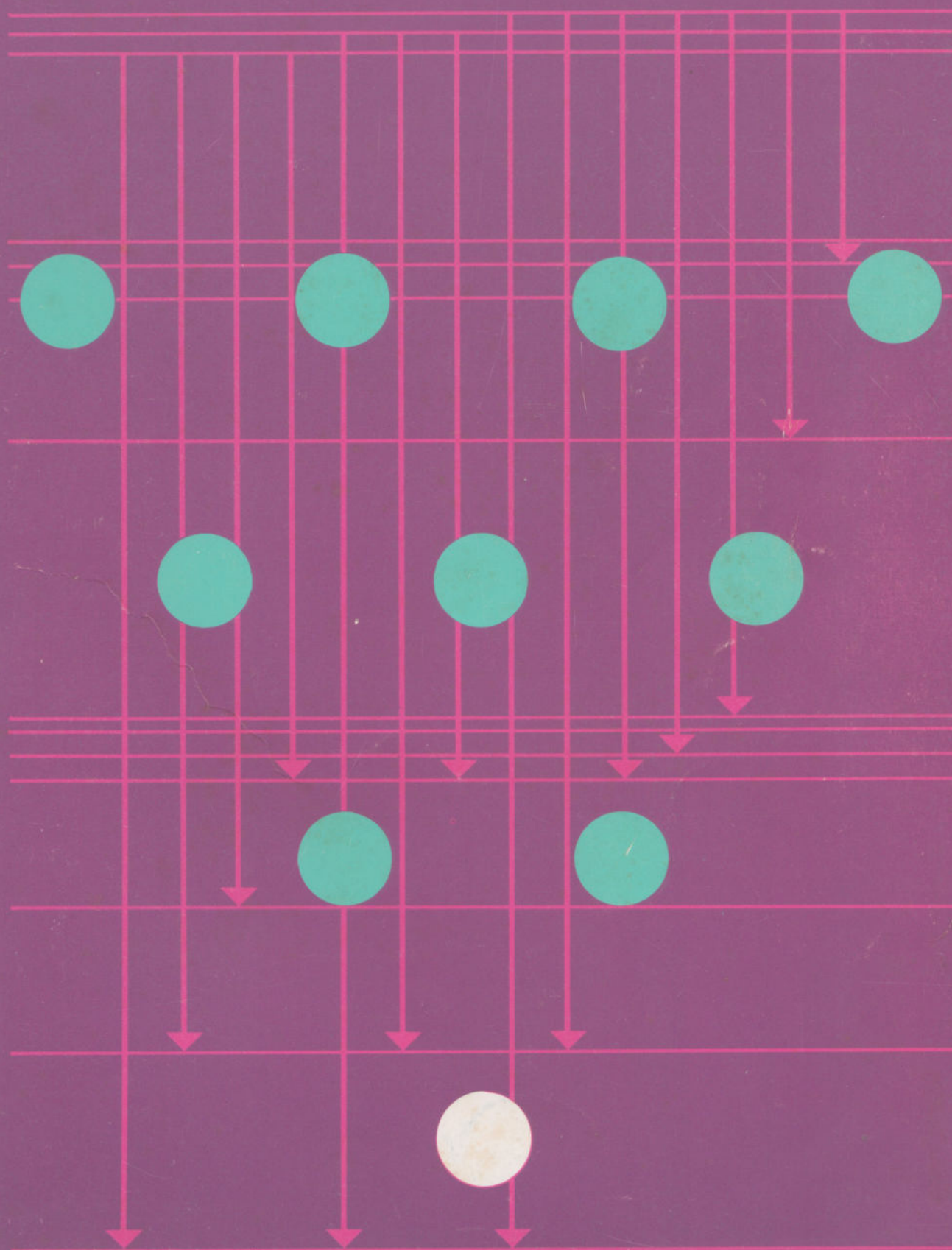




The Nucleus of the Atom

Elementary Particles





The Open University

Science Foundation Course Unit 31

THE NUCLEUS OF THE ATOM

Prepared by the Science Foundation Course Team

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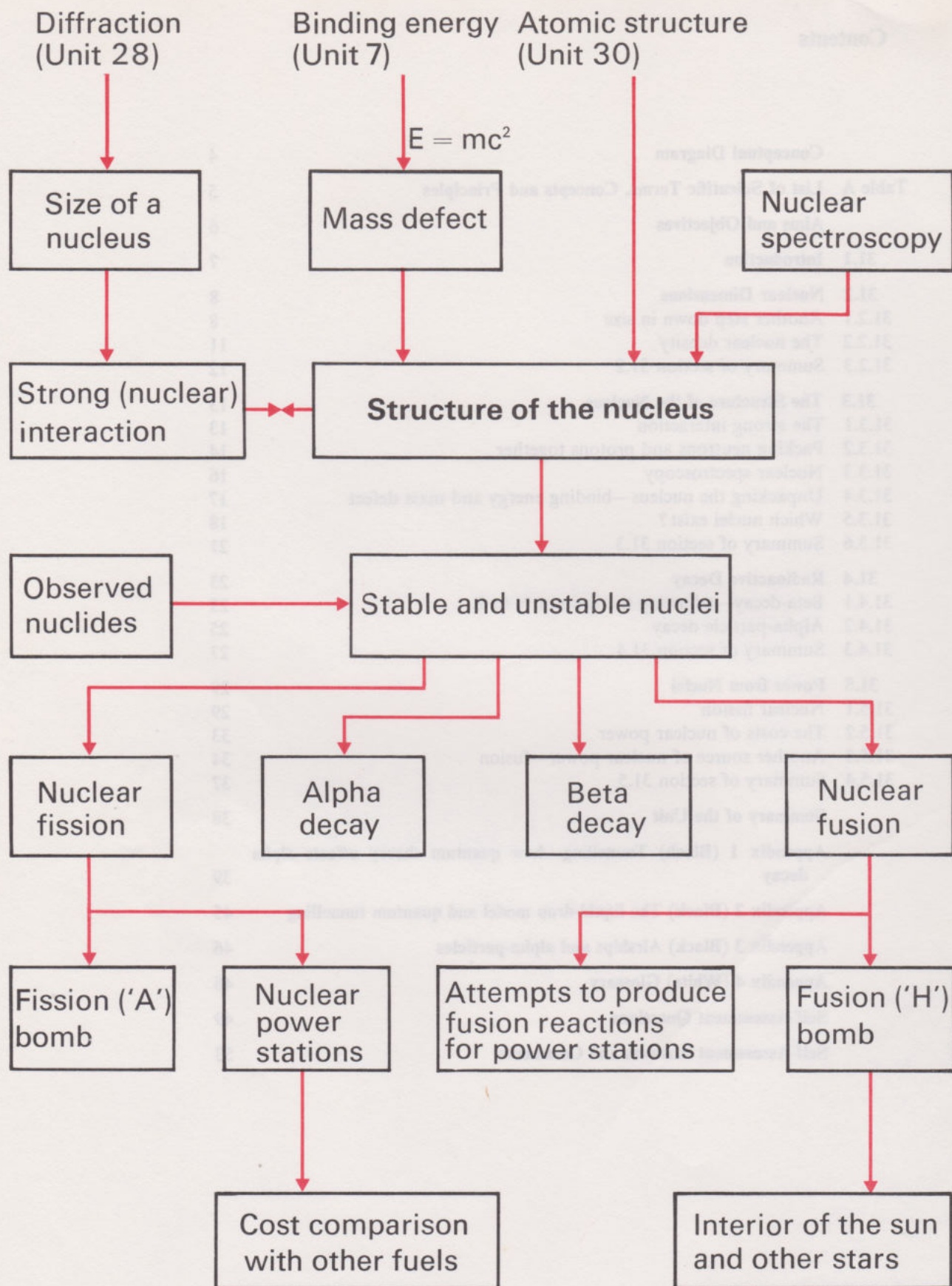


Table A

List of Scientific Terms, Concepts and Principles used in Unit 31

Taken as pre-requisites			Introduced in this Unit			
1	2		3	4		
Assumed from general knowledge	Introduced in a previous Unit	Unit No.	Developed in this Unit	Page No.	Developed in a later Unit	Unit No.
diameter	atom	3	effective nucleus radius	11		
	atomic nucleus	6	nucleon	11		
radius	electron wave	29	nucleon density	11		
	momentum	3	strong interaction charge			
volume	wavelength	2	independence	13		
	de Broglie formula	29	nucleon energy level	14		
density	nuclide	6	total nuclear binding energy	17		
	diffraction	2, 28	neutron excess	21		
	interference	28	positron	23		
	femtometre	HED	mean binding energy per nucleon	25		
	atomic mass number	6	radioactive series	27		
	proton	6	nuclear fission liquid-drop model	29		
	neutron	6	chain reaction	31		
	relative atomic mass	6	critical mass	31		
	energy	4	control rod	32		
	energy level	6	moderator	32		
	potential difference	4	nuclear fusion	34		
	electron-volt	4				
	ionization energy	6				
	atomic number	6				
	photon	6, 29				
	gamma-radiation	6				
	mass defect					
	rest energy	4				
	radioactivity	2				
	beta-particle	6				
	isotope	6				
	alpha-particle	6				
	half-life	2				

Any scientific terms used in this Unit but not listed above are marked thus † and defined in the glossary

Aims

- 1 To give an understanding of the atomic nucleus, its size and components, how it is held together, and which kinds of nuclei can exist.
- 2 To increase understanding about radioactive decay and in particular to link it with nuclear instability.
- 3 To introduce fission and nuclear fusion and thereby give some understanding of nuclear bombs and nuclear power stations. Also to consider the likely future of nuclear power as an economic proposition.

Objectives

When you have finished this Unit you should be able to:

- 1 Define correctly or recognize the best definition of each of the terms, concepts and principles in Column 3 of Table A.
- 2 Recognize true and false statements concerning the range of the 'strong interaction' force and the approximate size of nuclei.
- 3 Carry out simple calculations relating nuclear radius, atomic number, mean nuclear mass and mean nuclear density.
- 4 Identify from two angular scattering distributions the larger nucleus or the higher momentum beam; give reasons for the high momentum/energy needed.
- 5 Give brief evidence for, or recognize evidence for, neutron and proton energy levels in nuclei.
- 6 Summarize briefly, or recognize valid statements about, the limited range of numbers of protons and neutrons in observed nuclei, both stable and unstable; give reasons for the neutron excess in heavier nuclei.
- 7 Recognize examples of alpha decay, beta decay, gamma decay, fission and fusion which are either *possible* or *impossible* because of charge and nucleon conservation; predict which of β^+ - and β^- -decay is likely to occur in a given unstable nuclide from a knowledge of the stable nuclides with the same atomic mass number.
- 8 Explain from a graph of mean binding energy per nucleon (Fig. 8) why the following processes can take place with a release of energy:
 - (a) alpha decay or fission of many heavy elements;
 - (b) fusion of light elements.
- 9 Calculate the energy (in joules or MeV) released in alpha decay, fission or fusion, given the masses of relevant nuclides (in MeV/ c^2 or a.m.u.) and other appropriate constants.
- 10 Discuss in not more than two hundred words each, or recognize statements about, the relative economic factors of nuclear and conventional power stations, the social or ecological impact of nuclear and conventional power stations, and the likely nature of power stations in the long term.
- 11 Identify the contexts in which fusion is or could be important, and the problems which at present frustrate fusion power research.

31.1 Introduction.

This Unit will be concentrating on the tiny fragment, the nucleus, which carries most of the mass of an atom. Its very small size and great density can only be explained by a new force—the *strong interaction*. This force has a very short range, even smaller than the diameters of nuclei.

You know by now that many of the properties of the chemical elements are determined by the way their electrons are arranged in energy shells. Many properties of nuclei are accounted for in a similar way, because nuclei can also be regarded as possessing an energy-level structure—in fact two separate sets of levels, one set for protons and one for neutrons. Following on from a discussion of these levels, we can explain why only certain stable nuclides exist. Other nuclides exist with a slightly less restricted range of mass number and charge, but they are all unstable. These give rise to the phenomenon of radioactivity which you met in earlier Units. These forms of instability will be discussed in more detail than before.

The discussion will centre on the ability of the nuclear rest mass to convert into energy, as expressed in Einstein's equation $E=mc^2$. This consequence of relativity theory becomes particularly important in the context of the process of nuclear decay called fission. You will see how one fission process can lead to another in a self-perpetuating chain reaction in which large quantities of energy may be released. This reaction can be controlled, as in a nuclear power station, or it may lead to an explosion as in the 'A-bomb'. Fusion is another nuclear process which gives rise to energy release in particular to the energy of the H-bomb. The difficulties encountered in trying to harness this power for useful purposes are mentioned.

31.2 Nuclear Dimensions

31.2.1 Another step down in size

In Unit 6 you learned how very small atoms are. They are so small that it is barely possible to observe them directly. From the results of many measurements including X-ray diffraction from crystals, we deduce that atomic sizes are aroundångström unit, i.e. 10^{-10} m. The atomic nucleus is much smaller still. Its radius is a few times 10^{-15} m, though the exact size varies from one nuclide to another. How can we measure the size of atomic nuclei?

It is impossible to spread a film of bare nuclei on top of a bowl of water (as was discussed for atoms in Unit 6, section 6.12), or to make a crystal with bare nuclei packed tightly together. This is because nuclei are normally surrounded by the envelope of electrons which forms the outer part of an atom.

One technique for measuring nuclear sizes is the scattering of high-momentum particles—particularly electrons.

Why must they be high-momentum particles?

They must be high-momentum particles because, as you saw in Unit 2, the wavelength of the incoming beam (whether of ultra-sound from a bat trying to find a moth, of light in a microscope, or of electrons to observe nuclear sizes) must be smaller than—or comparable to—the size of the scatterer.

How are the momentum p and wavelength λ of any particle-wave related to each other?

The momentum p and the wavelength λ of any particle-wave are related by the de Broglie formula (Unit 29, equation 2):

$$p = \frac{h}{\lambda} \quad \dots\dots\dots (1)$$

If the wavelength λ of the beam is very small, the momentum p must be correspondingly large. In order to 'see' an object 10^{-15} m across, the wavelength of the beam must not be much greater than 10^{-15} m.

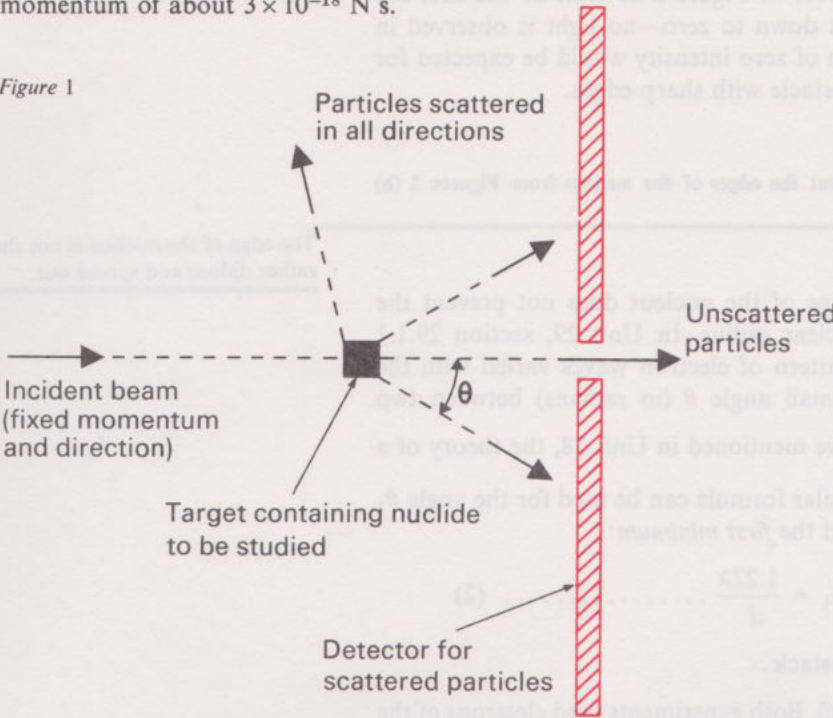
Given that Planck's constant $h = 6.6 \times 10^{-34}$ Js, calculate the momentum that such a beam of particles will have.

$$p = \frac{h}{\lambda} = \frac{6.6 \times 10^{-34}}{10^{-15}} = 6.6 \times 10^{-19} \text{ N s}$$

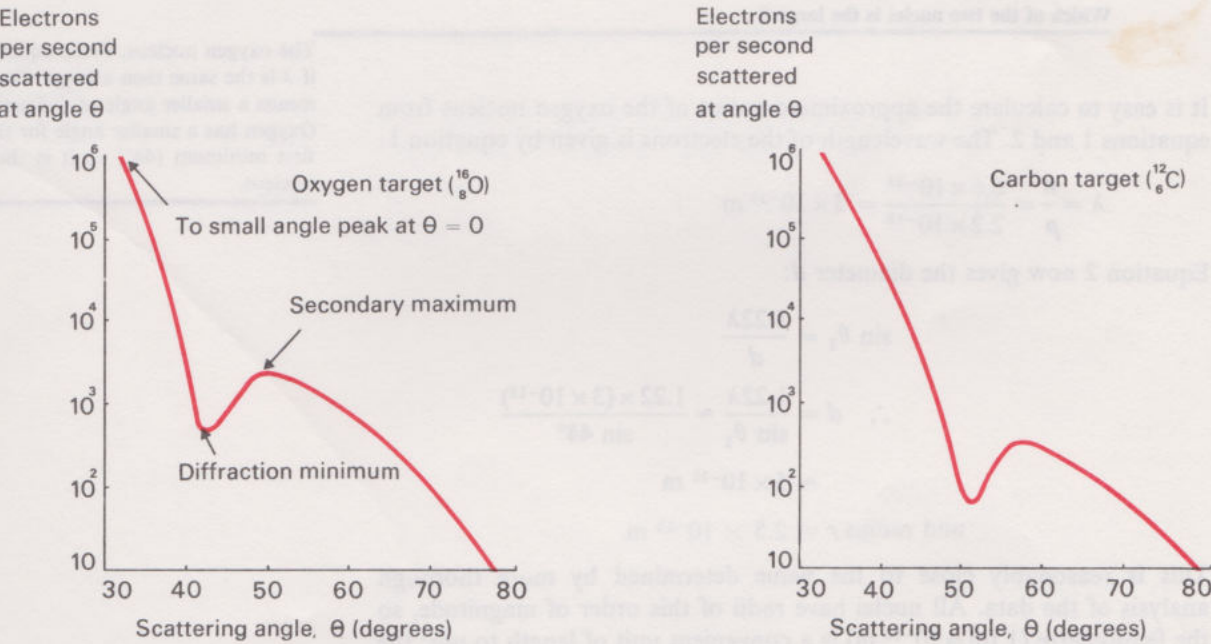
A momentum of the order of 10^{-19} N s may seem very small, but for a tiny particle like an electron it is very large. The electrons discussed in Unit 29, section 29.1 had a wavelength of 10^{-10} m, so their momentum was 10^5 times smaller than that of the high-momentum particles we are considering here.

Very high-momentum particles are produced by modern high-energy accelerators. In Unit 32 you will learn about the CERN proton synchrotron at Geneva, Switzerland. This machine can accelerate protons to a momentum of about 3×10^{-18} N s.

Figure 1



(a) A high-momentum scattering experiment.



(b) High-momentum electron scattering distributions for $^{16}_8\text{O}$ and $^{12}_6\text{C}$.

The size of the nucleus shows up in the angular distribution of the scattered beam. Figure 1 shows the experimental arrangement and results of a typical experiment. You will notice on Figure 1 (b), the increase of the scattering rate at smaller angles (the small angle diffraction peak), the sharp dip at $\theta = 44^\circ$ for oxygen and at $\theta = 51^\circ$ for carbon, and the secondary maximum at larger angles. The shape of the graphs represents an interference pattern in the electron wave, caused by diffraction round the

nucleus. You have seen similar effects in Figure 10 of Unit 28 and in Figure 4 of Unit 29. Figure 5 of Unit 29 shows the angular distribution of light waves diffracted through a slit; the pattern is very similar for an obstacle with sharp edges. However in Figure 5 of Unit 29 the first dip (diffraction minimum) goes right down to zero—no light is observed in this direction. A similar direction of zero intensity would be expected for electrons diffracting round an obstacle with sharp edges.

Can you guess anything about the edges of the nucleus from Figures 1 (b) and 1 (c)?

The edge of the nucleus is not sharp but rather diffuse and spread out.

The lack of sharpness of the edge of the nucleus does not prevent the measurement of an effective nuclear radius. In Unit 29, section 29.1.1 you saw how the interference pattern of electron waves varied with the separation d of two slits; the small angle θ (in radians) between two maxima was given by $\theta = \frac{\lambda}{d}$. As we mentioned in Unit 28, the theory of a circular obstacle shows that a similar formula can be used for the angle θ_1 between the *central maximum* and the *first minimum*:

$$\sin \theta_1 = \frac{1.22\lambda}{d} \dots\dots\dots (2)$$

where d is the diameter of the obstacle.

Now look at Figures 1 (b) and 1 (c). Both experiments used electrons of the same momentum (2.2×10^{-19} N s) and hence the same wavelength.

Which of the two nuclei is the larger?

It is easy to calculate the approximate radius of the oxygen nucleus from equations 1 and 2. The wavelength of the electrons is given by equation 1:

$$\lambda = \frac{h}{p} = \frac{6.6 \times 10^{-34}}{2.2 \times 10^{-19}} = 3 \times 10^{-15} \text{ m}$$

Equation 2 now gives the diameter d :

$$\begin{aligned} \sin \theta_1 &= \frac{1.22\lambda}{d} \\ \therefore d &= \frac{1.22\lambda}{\sin \theta_1} \approx \frac{1.22 \times (3 \times 10^{-15})}{\sin 44^\circ} \\ &\approx 5 \times 10^{-15} \text{ m} \end{aligned}$$

and radius $r = 2.5 \times 10^{-15}$ m.

This is reasonably close to the value determined by more thorough analysis of the data. All nuclei have radii of this order of magnitude, so the femtometre ($1 \text{ fm} = 10^{-15} \text{ m}$) is a convenient unit of length to use; the radius of the oxygen nucleus is about 2.5 fm.

This kind of analysis has been performed on data from electron scattering experiments with various nuclides in the target. The results can be summed up in one simple formula which is approximately true for the radius r of all but the lightest nuclei:

$$r = 1.2 A^{\frac{1}{3}} \text{ fm} \dots\dots\dots (3)$$

where A is the atomic mass number*.

* If you are unsure of the meaning of the index in $A^{\frac{1}{3}}$, see MAFS, section 1.A.5.

In Unit 6, section 6.2.2, you learned that A is equal to the sum of the total number of protons plus the total number of neutrons in a nucleus. Both protons and neutrons are called *nucleons*, so A is equal to the total number of nucleons.

31.2.2 The nuclear density

The volume V of a sphere is given by

$$V = \frac{4}{3}\pi r^3$$

For approximate calculations $\pi \approx 3$, so

$$V \approx 4r^3 \dots\dots\dots (4)$$

What is the volume of a sphere of radius 4 fm?

The density of a substance is the mass of a unit volume of that substance. In discussing nuclear densities it is convenient to use the number of nucleons in one cubic femtometre. This can be re-expressed as (mass per fm³) if it is multiplied by the average value of the mass of a nucleon.

From equation 4 the volume V is given approximately by:

$$V \approx 4r^3 = 4 \times (4)^3 \text{ fm}^3$$

$$\therefore V \approx 256 \text{ fm}^3.$$

$$\begin{aligned} \text{Now } V &\approx 4r^3 && \text{(equation 4)} \\ \text{and } r &= 1.2 A^{\frac{1}{3}} && \text{(equation 3)} \\ \therefore V &\approx 4 (1.2 A^{\frac{1}{3}})^3 = 6.9 A \end{aligned}$$

$$\begin{aligned} \text{Hence the average density } \rho &= \frac{A}{V} \text{ nucleons fm}^{-3} \\ &= \frac{A}{6.9A} \\ &= 0.14 \text{ nucleons per cubic} \\ &\quad \text{femtometre} \dots\dots\dots (5) \end{aligned}$$

How does the average nuclear density depend on the atomic mass number?

It doesn't. The average nuclear density is the same for all nuclei (except the smallest).

The mass of a proton or neutron is about 1.7×10^{-27} kg.
Estimate from equation 5 the ratio of the nuclear density and the density of water ($1\,000 \text{ kg m}^{-3}$).

1 fm³ is $(10^{-15})^3 \text{ m}^3$ or 10^{-45} m^3 . So the nuclear density expressed in SI units is

$$\begin{aligned} \rho &\approx 0.14 \times \left(\frac{1.7 \times 10^{-27}}{10^{-45}} \right) \text{ kg m}^{-3} \\ &\approx 0.24 \times 10^{18} \text{ kg m}^{-3} \\ \text{So } \frac{\rho_{\text{nuclear}}}{\rho_{\text{water}}} &\approx \frac{0.24 \times 10^{18}}{1000} \approx 2.4 \times 10^{14}. \end{aligned}$$

This is an enormous number and is a measure of how much ordinary matter could be compressed if all the atoms were squashed into their nuclei. Such a collapse of matter is believed to take place inside certain stars. A five millilitre teaspoonful of such material would have a mass of $1.2 \times 10^{12} \text{ kg}$ —about as much as Ben Nevis.

31.2.3 Summary of section 31.2

The size of a nucleus can be measured by observing the diffraction of a beam of electrons round the edges of the nucleus. The electrons must have a high energy and momentum so that their wavelength is small enough to be comparable with, or less than, the nuclear diameter. Experiments lead to radii of a few femtometres (10^{-15} m); for example, the radius of an oxygen nucleus is about 2.5 fm. All nuclei except the lightest have approximately the same nuclear density, so the volume of a nucleus is directly proportional to the number of nucleons (protons and neutrons) in it. This nuclear density is greater than the density of water by a factor of about 2.4×10^{14} . A large mountain, if it could be compressed so that all the nuclei of its atoms were touching, would fit on to a teaspoon.

Now turn to the Self-Assessment Questions and attempt numbers 1 and 2 (p. 49).

31.3 The Structure of the Nucleus

31.3.1 The strong interaction

In Unit 6 you learned that the nuclear mass is more than 99.98 per cent of the mass of an atom.

How are nuclear masses measured? If you cannot remember, refer to Unit 6, section 6.2.5.

You have seen how the comparatively small size and large mass of the nucleus leads to a very high density, about 2.4×10^{14} times that of water. Can this be accounted for from what we already know about the forces of nature? Gravitation is so weak that the systems it holds together are characteristically hundreds of miles across—or much more. The gravitational attraction between everyday objects, such as people, is negligible, even when they are close together. Yet very massive objects, like the Earth, have a gravitational attraction which is significant many thousands of miles away in space. In nuclei, the protons and neutrons are very close together, but they are also very light, so they exert infinitesimally small gravitational forces. Electrical attraction between protons and electrons maintains atoms which are about 10^5 times as big as nuclei. These forces cannot explain the density of nuclei; a new force has to be inferred, called the *strong interaction*. This force acts between nucleons, and is sufficiently powerful to hold them inside the tiny volume of the nucleus. The action of this force is very closely related to the elementary particles which are the subject of Unit 32. The strong interaction is approximately *charge independent*, i.e. the force is the same for two protons, two neutrons or one of each. Because of detailed quantum theory effects, there are no nuclides with just two neutrons bound together—but there is a nuclide with one neutron and one proton. This is called deuterium ${}^2_1\text{H}$ (or ${}^2\text{D}$). If a proton could be added to this it would stick, forming a helium isotope ${}^3_2\text{He}$. If instead, a neutron were added to ${}^2_1\text{H}$, it also would stick, forming ${}^3_1\text{H}$ —tritium, another isotope of hydrogen.

What practical problem can you anticipate in trying to add a proton to ${}^2_1\text{H}$? Why would it be easier to add a neutron?

The strong interaction or 'nuclear force' was first mentioned in Unit 4, section 4.2.3. It was argued there that it must be a short-range force, if it could influence objects some distance away from the immediate region of the nucleus, it would swamp the effects of the gravitational and electromagnetic forces. This short range is consistent with the small size of the nucleus. It also helps to explain why the density of large nuclei is independent of the mass number A . In Figure 2 you can see how a nucleon deep inside a large nucleus is acted upon by the short-range force (range ≈ 2 fm) of its nearest neighbours. It doesn't matter much what kind of nucleus the nucleon is in. The protons and neutrons always have similar properties, so the range and strength of the force are the same. The nucleons therefore pack themselves together with about the same density

strong interaction

charge independence

To add a proton to a nucleus it is necessary to overcome the long-range electrical repulsion between the positive charge of the proton and the positive charge of the nucleus. A neutron has no charge, so it experiences no electrical repulsion as it approaches a nucleus.

in nuclei of differing sizes. Only in the surface regions is there any variation in the forces on individual nucleons.

Figure 2 shows, schematically, the strong interaction forces acting on two nucleons A and B. Notice that the forces on A balance, but B is pulled inwards. Also A has links with three other nucleons, while B has links with only two.

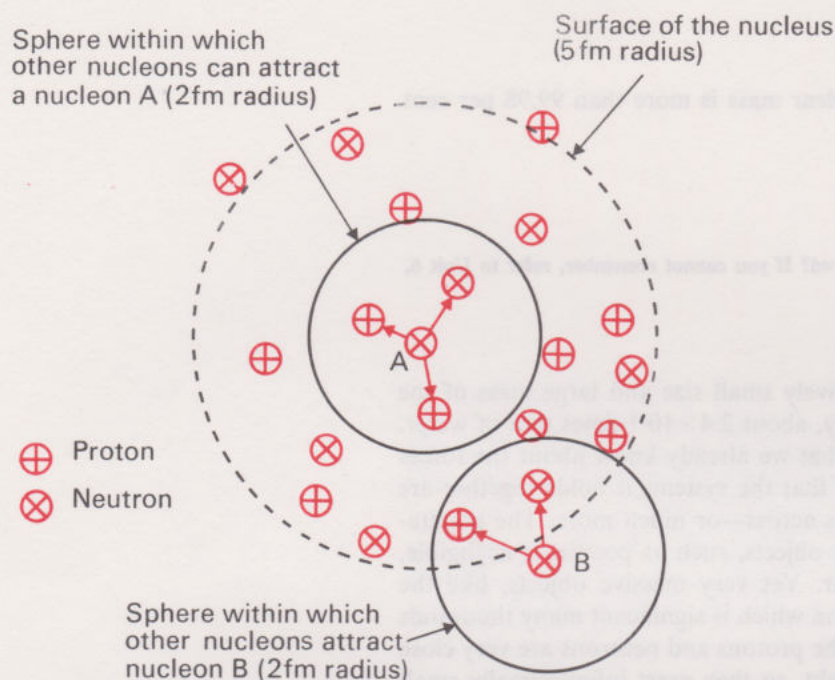


Figure 2 The strong interaction forces on different nucleons.

31.3.2 Packing neutrons and protons together

In Units 6, 7 and 30, you have become familiar with the energy levels that are available to electrons when they are packed together in an atom. There is strong evidence that nucleons also have a structure of energy levels within the nucleus. However this structure is created by the strong interaction which is not yet fully understood.

What is the difference between the binding energy of a nucleon and the ionization energy of an atomic electron?

The two quantities have essentially the same physical significance, but very different typical values. The ionization energy of an atomic electron will be in the region of 10^{-19} joule: 22×10^{-19} J for the ground state of hydrogen for example. This means that the binding energy of this electron—the energy the atom would need to be turned into an H^+ ion—is 22×10^{-19} J.* Binding energies are often expressed in units called electron-volts; one electron-volt (1eV) is the energy an electron (or proton) acquires when accelerated through a potential difference of one volt, and

* The ionization energy of an atomic electron is the amount of energy it has to be given to remove it from the atom. Another way of saying the same thing is that the atomic electron is bound to the atom with a 'binding energy' equal (numerically) to its ionization energy.

An analogy might perhaps help you to understand this idea. Suppose you are put in prison because you can't pay bail of £5. It needs £5 to bail you out. You are kept in by a lack of £5. That £5 you haven't got is your 'binding money', and if someone supplies it and you get let out, then the £5 he supplies is your 'ionization money'.

is equal to 1.6×10^{-19} J (see Unit 4, section 4.4.3). The binding energy of the electron in a hydrogen atom in its ground state is 13.6eV. The binding energy of a nucleon in a nucleus is roughly a million times bigger than this; 6.75MeV for the first neutron to be removed from $^{21}_{10}\text{Ne}$, for example.

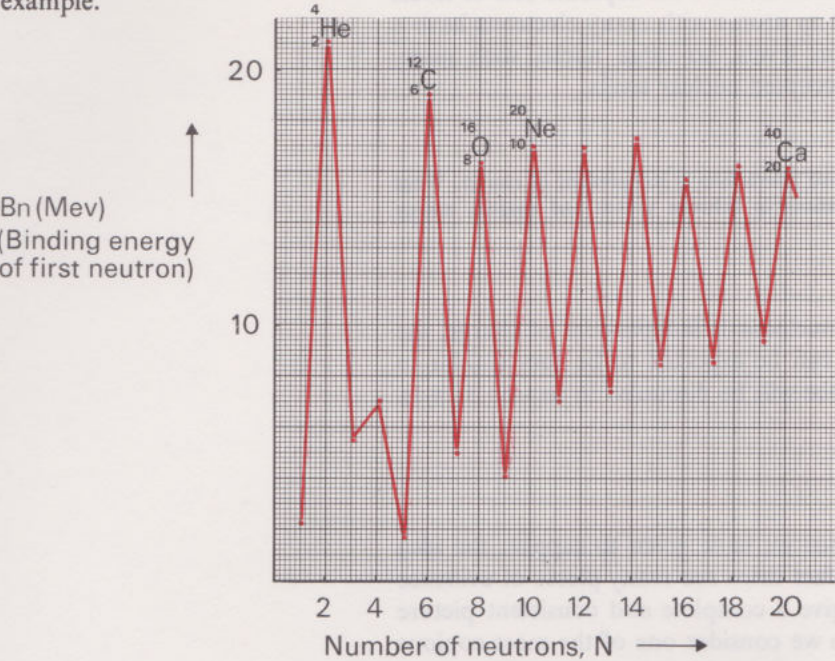


Figure 3 The binding energy of the first neutron plotted against the number of neutrons N.

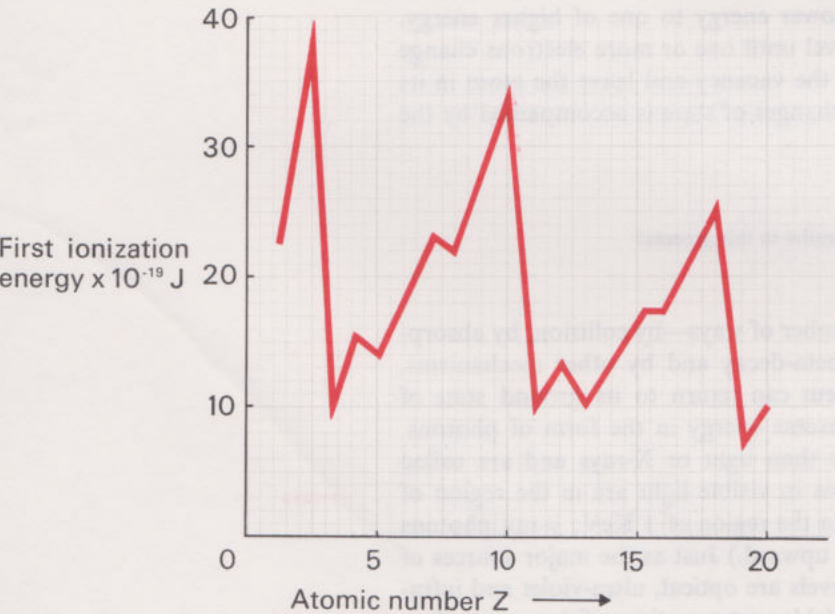


Figure 4 The ionization energy (of the first electron) plotted against atomic number.

Figure 3 is a plot which looks very similar to Figures 4 and 5 of Unit 7. (Figure 5 of Unit 7 is repeated here as Figure 4.) Figure 3 is a plot of the energy which would be required to remove the first neutron from each of a whole series of nuclei (the binding energy). This is plotted against the number of neutrons, N, in each nucleus.

What are the most obvious similarities between Figures 3 and 4?

Both of these plots are very jagged and the peaks are always at even numbers. Clearly, some kind of energy-level structure is indicated for neutrons.

Proton binding energies vary with the number of protons Z in a very similar way to the variation of neutron binding energies with N in Figure 3. So protons appear to have an energy-level structure too. The theory of these levels is worked out in a similar manner to the theory of atomic electron energy levels, but in the nucleus there are separate sets of levels for neutrons and for protons. Just as atoms with many electrons have a number of fully occupied electron levels, so large nuclei with many nucleons have a number of fully occupied nuclear levels.

It has been stated that the strong interaction is independent of charge. What does this imply about the relationship between proton and neutron energy levels?

Since the major force binding the nucleons is independent of charge, the proton and neutron energy levels can be expected to be very similar to one another (an important difference will be discussed in section 31.4.1).

31.3.3 Nuclear spectroscopy

So far, Figure 3 is the only evidence we have given to support the idea of energy levels in the nucleus. In fact there are many pieces of evidence which can be pieced together to give a complete and consistent picture of the energy levels. In this section we consider one of the most copious sources of this evidence.

When an *atom* is *excited* by a collision or by absorption of a photon, an electron changes from a state of lower energy to one of higher energy. This leaves a vacancy in a lower level until one or more electrons change state downwards (in energy) to fill the vacancy and leave the atom in its ground state again. Each of these changes of state is accompanied by the radiation of a photon of light.

Can you think of the nuclear parallel to this process?

Nuclei may become excited in a number of ways—by collision, by absorption of a photon, as a result of beta-decay and by other mechanisms. One way in which an excited nucleus can return to its ground state of lowest energy is by radiating the excess energy in the form of photons. These photons have higher energy than light or X-rays and are called *γ -rays*. (The energies of the photons in visible light are in the region of 1 eV; X-ray photons have energies in the region of 1 KeV; γ -ray photons have energies from about 0.2 MeV upward.) Just as the major sources of information about atomic energy levels are optical, ultra-violet and infrared spectra, so γ -ray spectroscopy yields vast quantities of data on nuclear energy levels.

Figure 5 shows some of the observed energies of γ -rays emitted from excited ${}^{31}_{15}\text{P}$. The horizontal lines represent energy levels in MeV above the ground state, and the length of each vertical line gives the energy of a particular γ -ray spectral line. Compare Figure 5 with the diagrams (in Unit 6, section 6.5.2 and Unit 7, 7.2) of energy levels in many-electron atoms. In Unit 6, you learned that when an electron ‘jumps’ from one energy level to another inside an excited atom, a photon is emitted. Similarly in a nucleus, when a nucleon ‘jumps’ from one energy level to another a γ -ray photon is emitted. This diagram is very similar to Figure 7 in Unit 6, though the photon energies here are a million times larger than the energies of photons emitted by the hydrogen atom.

γ -rays

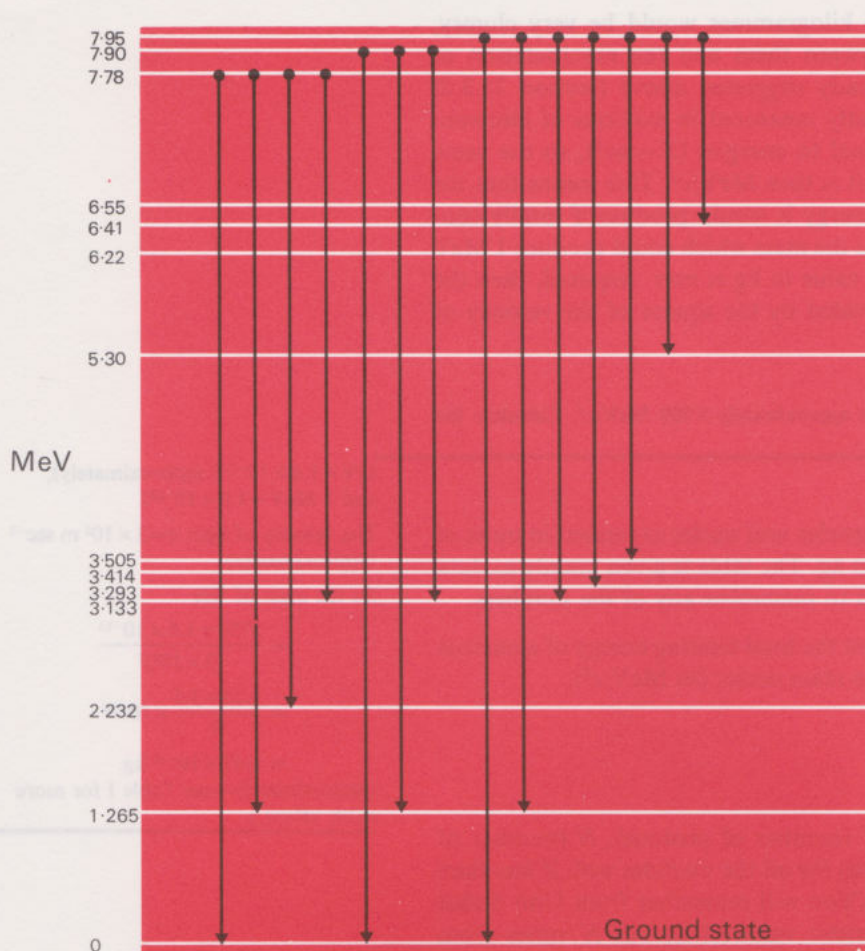


Figure 5 Some energy levels and transitions in $^{31}_{15}\text{P}$.

31.3.4 Unpacking the nucleus—binding energy and mass defect

How much energy would be required to pull a nucleus apart, one nucleon at a time?

A certain amount of energy will be needed to remove each nucleon, in turn, from the nucleus. The sum of all these energies is the amount of energy required to take the nucleus completely apart. This is the *total binding energy* of the nucleus—the energy required to remove all of its nucleons to a large distance from one another—out of range of the strong interaction and to a separation where electrostatic interactions are negligible. The total binding energy of a nucleus is a concept you met briefly in Unit 6. It gives rise to the *mass defect* which can be measured with a mass spectrometer. Thus, bearing in mind that mass and energy are equivalent quantities (Unit 4, rest mass energy = M_0c^2), the binding energy of the nucleus is that amount of energy which is equivalent to the mass defect of the nucleus, using the relativistic formula $E = Mc^2$.

You will remember that in Unit 6, section 6.2.6, the mass defect of a nucleus was defined as the difference between its mass and the masses of its constituent nucleons. When a structure is bound together, energy is needed to pull it apart and this energy is equal in magnitude to the total binding energy. So the total binding energy is equal to the reduction in mass of the bound system. In studying nuclear physics, there are many processes in which part of the mass of some object becomes available in the form of kinetic energy, or in which energy is absorbed, so increasing the mass of an object. It is therefore convenient to work in a system of units in which the mass-energy equivalence is easily expressed.

total binding energy

mass defect

To use the SI units of joules and kilogrammes would be very clumsy, requiring repeated conversions between them and the manipulation of large powers of ten. We have already suggested above (section 31.3.2) that nuclear energies are conveniently measured in millions of electron-volts (MeV). Masses are proportional to energies ($E=mc^2$), so the same basic unit can be used; the mass unit is then MeV/c^2 . This means that the mass is expressed in terms of the energy it would produce if totally converted. A mass of one MeV/c^2 means the mass which could produce 1 MeV of energy if totally converted; if a value in kg is ever required, then the MeV is converted to joules and divided by the square of the velocity of light.

The mass of the ${}^4_2\text{He}$ nucleus is approximately $3750 \text{ MeV}/c^2$. Calculate the equivalent mass in kg.

Table 1 gives the masses of some particles and nuclei expressed in units of MeV/c^2 , in atomic mass units, and in kg. The table is given mainly as data for the SAQs. You are not expected to remember any of the numbers.

One advantage of using MeV/c^2 is that the total binding energy of a nucleus (in MeV) is numerically equal to the mass defect (in MeV/c^2).

31.3.5 Which nuclei exist?

Figure 6 (a) shows the values of Z (number of protons), N (number of neutrons) and A (number of nucleons) for all the nuclides with Z less than 31 which have ever been observed. (You will remember from Unit 6 that each element has its own characteristic value of Z , but N varies from isotope to isotope of the element.)

$1\text{eV} = 1.6 \times 10^{-19}\text{J}$ (approximately),
and $1 \text{ MeV} = 1.6 \times 10^{-13}\text{J}$
The velocity of light $c = 3 \times 10^8 \text{ m sec}^{-1}$
(approximately)
So the mass of ${}^4\text{He}$
$$= \frac{3750 \times 1.6 \times 10^{-13}}{(3 \times 10^8)^2}$$
$$= \frac{3.75 \times 1.6}{9} \times 10^{-26}$$
$$= 6.67 \times 10^{-27} \text{ kg}$$

(approximately—see Table I for more exact values.)

Figure 6
(a) Known nuclides with $Z \leq 30$.

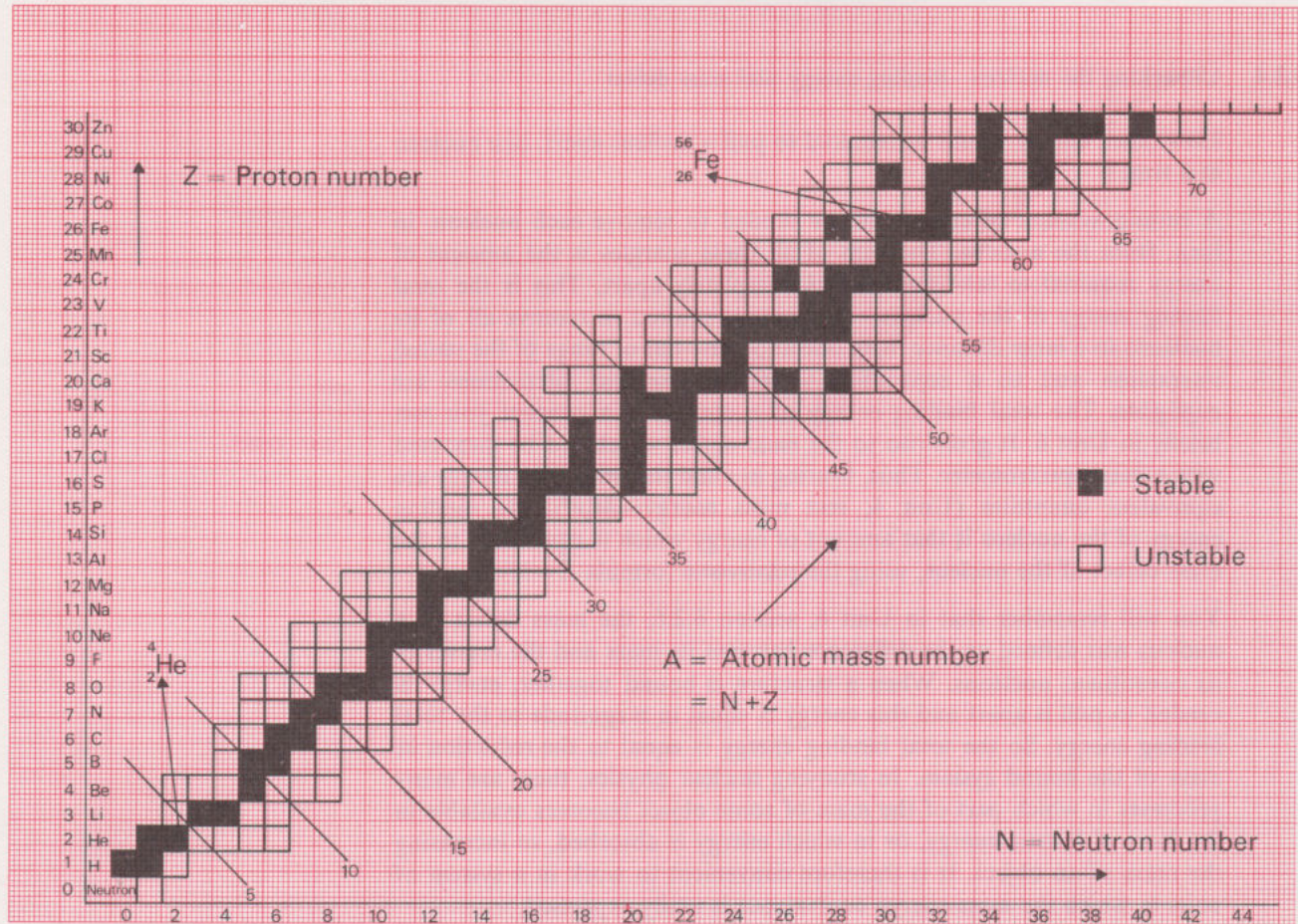


Table 1 Masses of some Particles and Nuclides*

Symbol	Name	Stable or unstable	Mass in MeV/c^2	Mass in atomic mass units (a.m.u.)	Mass in kilogrammes	Binding energy per nucleon of stable nuclides	Comment
e	electron	stable	0.51106	0.000549	9.109×10^{-31}	—	
p	proton	stable	938.256	1.0073	1.6726×10^{-27}	0	
n	neutron	unstable	939.550	1.0087	1.6748×10^{-27}	(0)	decays $n \rightarrow p + e^- + \nu$
${}^1_1\text{H}$	hydrogen	stable	938.767	1.0078	1.6734×10^{-27}	0	$p + e^-$
${}^2_1\text{H}$	deuterium (heavy hydrogen)	stable	1876.1	2.0014	3.3231×10^{-27}	1.1	least tightly bound stable nuclide
${}^4_2\text{He}$	helium	stable	3749.1	4.0026	6.6459×10^{-27}	7.1 MeV	α -particle + $2e^-$
${}^6_2\text{He}$	helium	unstable	5607.5	6.0189	9.9938×10^{-27}	5.2 MeV	Same A value
${}^6_3\text{Li}$	lithium	stable	5604.0	6.0151	9.9875×10^{-27}		
${}^8_4\text{Be}$	beryllium	unstable	7457.0	8.0053	1.3292×10^{-26}	7.6 MeV	decays to 2 α -particles
${}^{12}_6\text{C}$	carbon	stable	11178.0	12.000	1.9925×10^{-26}		
${}^{14}_7\text{N}$	nitrogen	unstable	14910.0	16.0038	2.6630×10^{-26}	8.0 MeV	Same A value
${}^{16}_8\text{O}$	oxygen	stable	14899.0	15.9949	2.6558×10^{-26}		
${}^{56}_{26}\text{Fe}$	iron	stable	52102.0	55.9249	9.2875×10^{-26}	8.8 MeV	One of the most tightly bound of all the nuclides
${}^{232}_{90}\text{Th}$	thorium	unstable	2.1607×10^4	231.9618	3.8515×10^{-25}	(7.6 MeV)	α -emitter
${}^{238}_{92}\text{U}$	uranium	unstable	2.1886×10^4	234.9561	3.9012×10^{-25}		α -emitter and fissionable
${}^{235}_{92}\text{U}$	uranium	unstable	2.2164×10^4	237.9492	3.9509×10^{-25}		α -emitter and fissionable

* This data is taken from a number of sources. There is some variation on the least significant figures, especially for unstable nuclides. Note that for complete atoms the mass given is that of the neutral atom including its electrons. The unit of mass, MeV/c^2 , is explained in section 31.3.4.

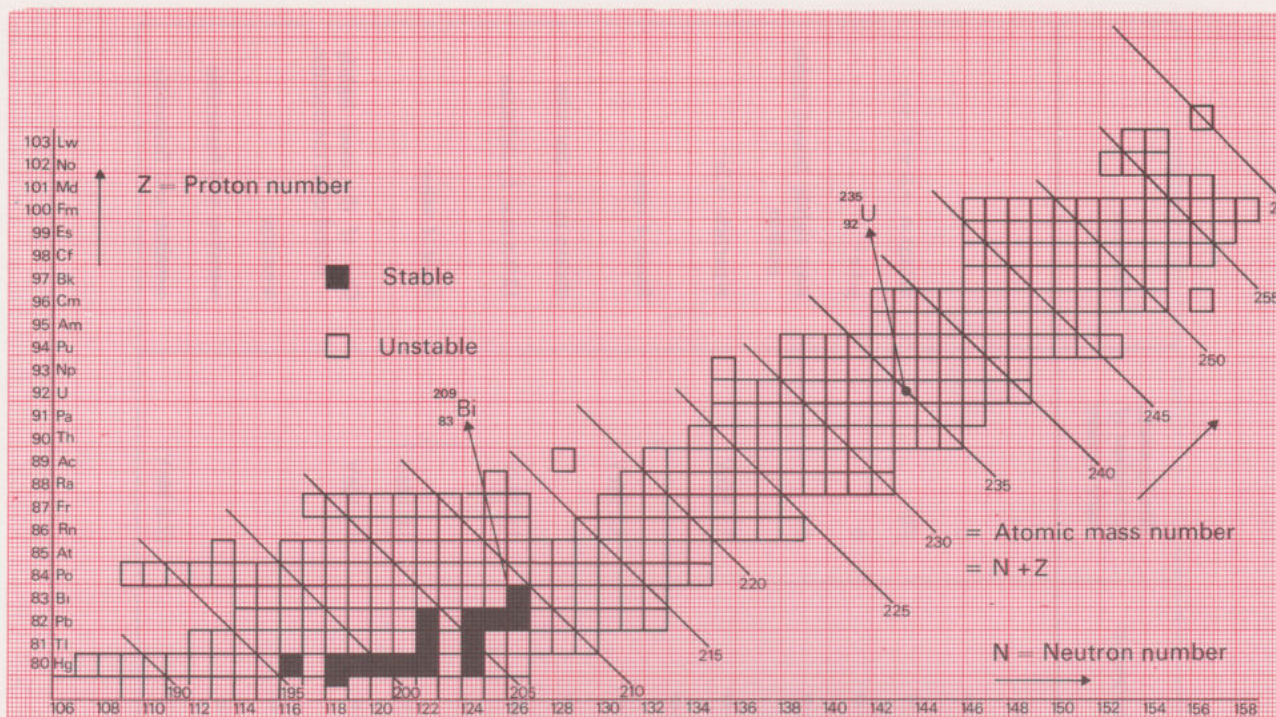


Figure 6 (b) Known nuclides with $Z \geq 80$.

Figure 6 (b) shows the nuclides which have been observed with Z greater than 79. There are, of course, many other nuclides between $Z=30$ and $Z=80$. All we want you to notice at the moment is that some of the nuclides in Figures 6 (a) and 6 (b) are stable (shown shaded), but many are unstable (shown unshaded) and decay (by alpha- α) or beta- β) radiation). Most of the nuclei in Figure 6 (b) (high Z) are unstable.

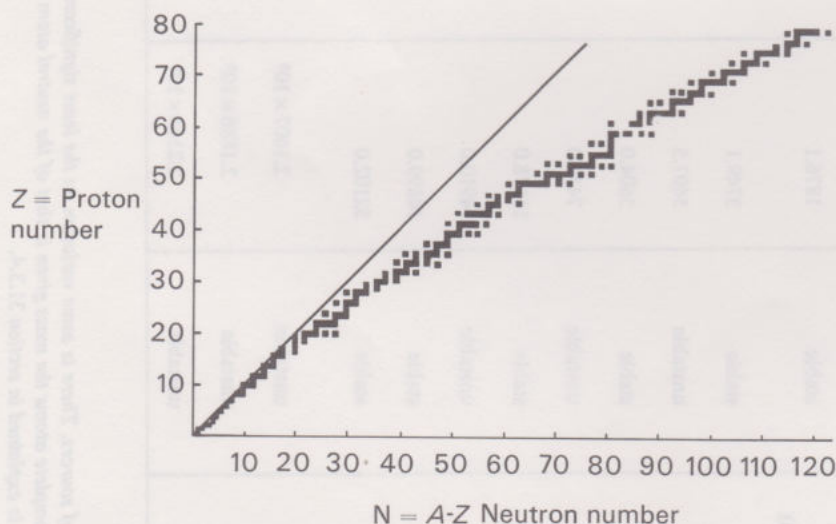


Figure 6 (c) Plot of stable nuclides with $Z < 80$.

The vertical axis of each chart gives the number Z of protons in the nucleus. The horizontal axis gives the number of neutrons, $N=A-Z$. Figures 6 (a) and 6 (b) are complicated and incomplete, so it is difficult to see the broad outlines of the picture. Figure 6 (c) is a simpler plot with stable nuclides only up to $Z=80$. Notice that they form a narrow band. Each nuclide is plotted as a small square against the proton number (Z) and

the neutron number (N). The full line is at 45° to each axis.

For a given Z , what is the stable value of N likely to be? Does the ratio of Z to N for stable nuclei vary with position in the band? Does the observed stable band go on and on as Z increases?

For a given Z , up to around 20, N is roughly equal to Z in the stable band. As Z increases above 20, N increases somewhat faster than Z . Apparently, heavy nuclei need more neutrons for stability. Thus for

$${}^{16}_8\text{O (oxygen)}, \quad \frac{Z}{N} = \frac{8}{8} = 1.0$$

$$\text{and for } {}^{40}_{20}\text{Ca (calcium)} \quad \frac{Z}{N} = \frac{20}{20} = 1.0$$

$$\text{but for } {}^{56}_{26}\text{Fe (iron)}, \quad \frac{Z}{N} = \frac{26}{30} = 0.866$$

$$\text{for } {}^{107}_{47}\text{Ag (silver)}, \quad \frac{Z}{N} = \frac{47}{60} = 0.783$$

$$\text{and for } {}^{208}_{82}\text{Pb (lead)}, \quad \frac{Z}{N} = \frac{82}{126} = 0.65$$

(Each of the above examples is the most abundant isotope of the element mentioned.)

For the heavier stable nuclei, we say there is a *neutron excess* of $N - Z$. Finally, at $Z = 83$ (bismuth) we find the last stable nucleus. At higher values of Z there are some nuclides such as uranium and radium which occur naturally, but all of them are radioactive. They decay with time and (as you saw in Unit 2, section 2.5.4, and in Unit 23, section 23.5.2) they give us important techniques for measuring the age of the Earth and the solar system. Above $Z = 105$, no further nuclides have been found or made, though a few more very short-lived examples may yet be produced in the laboratory.* So we find that only a very limited number of nuclei exist. Nucleons cannot be added together indefinitely to make extremely large nuclei, and even with moderately-sized nuclei there are strict limitations on the permitted range of values for the ratio of the number of neutrons to protons. This at first seems rather strange. After all, we have so far thought of the nucleus as consisting of two almost independent systems—an energy-level structure for neutrons and another for protons. How then can the number of protons in the proton energy-level structure affect the number of neutrons to be found at each neutron energy level? Why not have a nucleus with 50 neutrons and no protons, for example? The next section is concerned with explaining why the neutron to proton ratio has only limited values; the two subsequent sections deal with the problem of why there are no extremely large nuclei.

neutron excess

31.3.6 Summary of section 31.3

The nucleus of an atom is held together by a force between nucleons called the 'strong interaction'. Its range is very short (about 2 fm) and it is charge independent—i.e. it does not distinguish between protons and neutrons. Within this short range the strong interaction completely dominates electrical and gravitational forces. The neutrons inside a nucleus are

* Note added in March 1971. A recent experiment claims to have observed a nuclide with $Z = 112$.

distributed among a series of energy levels analogous to the energy levels of electrons in an atom; protons have a similar but separate set of energy levels.

The evidence for nuclear energy levels comes from nuclear spectroscopy. A nucleon is raised to a higher energy level; when it returns to its original stable level it emits a photon of gamma radiation having an energy corresponding to the difference between the two energy levels. The process is analogous to the production of spectral lines of atomic spectra, but the energies involved are much larger.

The nuclear binding energy is equal to the energy which would have to be put back into the nucleus in order to pull it apart into separate nucleons. This binding energy shows itself as a mass defect; the mass of the nucleus is less than that of its constituent nucleons. The binding energy and the mass defect are related by Einstein's equation.

Observed nuclides have a limited range of values of the number of protons (Z) and the number of neutrons (N). For nuclides with Z up to about 20, N is roughly equal to Z . Larger nuclides have a neutron excess. The largest stable nuclide is bismuth with $Z=83$. Above this, all nuclides are radioactive. Above $Z=112$ no nuclides have yet been observed.

Now turn to the Self-Assessment Questions and attempt numbers 3, 10 and 11 (pp. 49, 52).

If you wish to follow up topics mentioned in this section, the following two books might be useful.

T. Littlefield and N. Thorley, *Atomic and Nuclear Physics*, Van Nostrand, 1968.

J. Fremlin, *Applications of Nuclear Physics*, English U.P., 1964.

31.4 Radioactive Decay

31.4.1 Beta decay—adjusting the ratio of N to Z

We begin by considering nuclear binding energies. Because nuclear binding energies are so large, slight differences in the energy levels of protons and neutrons show up as measurable differences in the atomic mass.*

How is the mass of a nucleus different from the mass of the corresponding nuclide?

The mass of the nucleus will be equal to the atomic mass *minus* Z times the electron mass.**

Write down an expression for the energy equivalent of the total rest-mass of a nucleus containing Z protons and N neutrons, in terms of the mass of a proton, the mass of a neutron, and the mass defect.

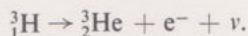
The total rest energy is the total rest mass of a nucleus $\times c^2$. This is equal to (the mass of Z protons plus the mass of N neutrons minus the mass defect) $\times c^2$. In Figure 7, we show the value of the total rest energy of the nucleus for a series of nuclides that have $A = 101$.

Notice that the variable along the bottom of the graph is Z , so that each of the values plotted is for a different element. The chemical symbol for the element is included in each case below its Z value.

In Figure 7 there are arrows labelled β^+ and β^- which lead down the slope on either side and end at the black dot of $^{101}_{44}\text{Ru}$, which is the lowest of all the dots. You met β^- in Unit 6. When a nucleus undergoes β^- -decay it emits an electron. It also emits a neutral particle called a neutrino (denoted by the Greek letter Nu, ν). The neutrino is not a nucleon and its loss does not change Z , N or A . We shall more or less ignore it for the moment, though it will always be written in a decay formula. For instance β^- -decay in any nucleus can always be regarded as the decay of a bound neutron (denoted by n) into a proton (denoted by p) an electron (denoted by e^-) and a neutrino. This decay is written:



Similarly the β^- -decay of tritium ^3_1H is written:



Some nuclei decay by β^+ -decay. This is the emission of a positive electron—a *positron* (denoted by e^+). It is a particle having the opposite charge but

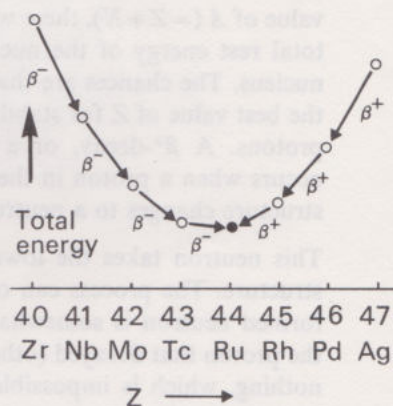


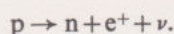
Figure 7 Total energy of the nucleus plotted against Z for a group of nuclides with $A = 101$.

* For instance, $^{12}_6\text{C}$ has a total binding energy of about 91 MeV. A difference of as little as one per cent in this amount of energy (due to a slight 'excitation' of the nucleus, in which one or more nucleons are not in their most tightly bound, lowest energy levels) would be 0.91 MeV. This is nearly double the rest energy of an electron (0.51 MeV). It would show up as an increase of the mass of the nucleus by an amount nearly equal to the rest mass of two electrons. This would certainly be measurable.

** Electron binding energies are very small compared with the electron rest energy, so we can neglect them.

positron

the same mass as a negative electron. The basic reaction in β^+ -decay is:



What would you expect to be the effect of β^+ emission on the mass number and atomic number of the nucleus?

The mass number would remain the same but the nuclear charge would decrease by one unit; i.e. the atomic number Z would decrease by one unit. β^+ -decay does not happen in naturally occurring nuclides, but it is common among the short-lived isotopes produced by modern techniques. Thus, when an artificially produced atom of $^{101}_{47}\text{Ag}$ decays by β^+ -emissions, it forms a different nucleus.

Which element? Which isotope?

From Figure 7 you can see that the answer is $^{101}_{46}\text{Pd}$.

You now have the evidence. What do you think is the explanation of the absence of nuclides away from the stable band of Figure 6 (c)?

The reason is that, although they can be formed, they decay so quickly that they are rarely found in nature.

In the collision of a beam of particles from an accelerator, or in the centre of a star, a group of Z protons and N neutrons may come close together and stick to form a nucleus. For this total number of nucleons, i.e. this value of $A (=Z+N)$, there will be just one region of values of Z where the total rest energy of the nucleus is close to a minimum, giving a stable nucleus. The chances are that the group of nucleons will not at first have the best value of Z for stability. If Z is too big, the nucleus has too many protons. A β^+ -decay, or a series of them, will correct this. β^+ -decay occurs when a proton in the highest occupied energy level of the proton structure changes to a neutron (see Fig. 8 (a)).

This neutron takes the lowest vacant place in the neutron energy-level structure. The process can only happen if the energy level for the newly formed neutron is somewhat lower than the level formerly occupied by the proton that decayed (otherwise energy would have been created out of nothing, which is impossible). If Z on the other hand is too small, the nucleus has too many neutrons and β^- -decay will bring it back to the stable region.

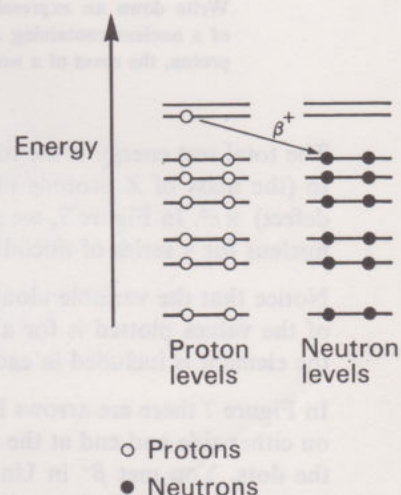
In β^- -decay, what kind of transition is made?

β^- -decay occurs when a neutron in the highest occupied neutron level can drop to a lower energy by becoming a proton (see Fig. 8 (b)).

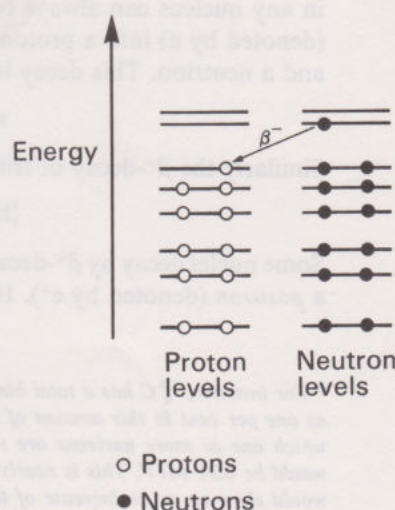
You may be worried that the total energies of different nuclides shown in Figure 7 are not directly comparable because of the rest energy of the β -particle emitted. Detailed calculations include this and the values of the figure have been corrected to allow for it.

What relation do you notice between the value of Z at the minimum in Figure 7 and the value of the atomic mass number $A=101$?

Figure 8



(a) A simplified picture of the nuclear energy levels in β^+ -decay.



(b) A simplified picture of the nuclear energy levels in β^- -decay.

At this particular value of A , the most stable value for Z corresponding to the minimum total energy of the nucleus is 44, that is somewhat less than $A/2$. This is the effect you saw in Figure 6 (c). The stable band swings away from the line $Z=N$, giving a neutron excess in heavy nuclei. In light nuclei stability occurs when $Z=N=\frac{1}{2}A$ (approximately). Apparently neutrons and protons have a very similar energy-level structure when Z is less than 20. But when Z increases beyond 20, the electrical repulsion between the protons has an ever-increasing effect. The energy levels that are available to protons are raised above the equivalent levels for neutrons.* Thus, even when there are more neutrons than protons in the nucleus (as in $^{101}_{47}\text{Ag}$, $^{101}_{46}\text{Pd}$ and $^{101}_{45}\text{Rh}$ in Figure 7), the highest occupied proton level can be higher than the available neutron levels, and β^+ -decay can take place.

Now we have explained why the band of stable nuclei in Figure 6 is quite narrow and why it veers off towards a neutron excess at higher values of Z and N . But why does the band stop? We must next explain why there are no stable nuclides above $^{209}_{83}\text{Bi}$, and no known unstable ones above $Z=112$.

31.4.2 Alpha-particle decay

Look at Figure 9 and try to work out an explanation for the upper limit on nuclear masses from the behaviour of the mean binding energy per nucleon.

You will notice that the *mean binding energy per nucleon* reaches a maximum around $A=65$ and then falls off towards $A=240$. The mean binding energy per nucleon is just the total binding energy of the nucleus divided by the number of nucleons A . Notice how prominent the nuclei ^4_2He , $^{16}_8\text{O}$ and $^{12}_6\text{C}$ are. These nuclei are particularly stable.

mean binding energy per nucleon

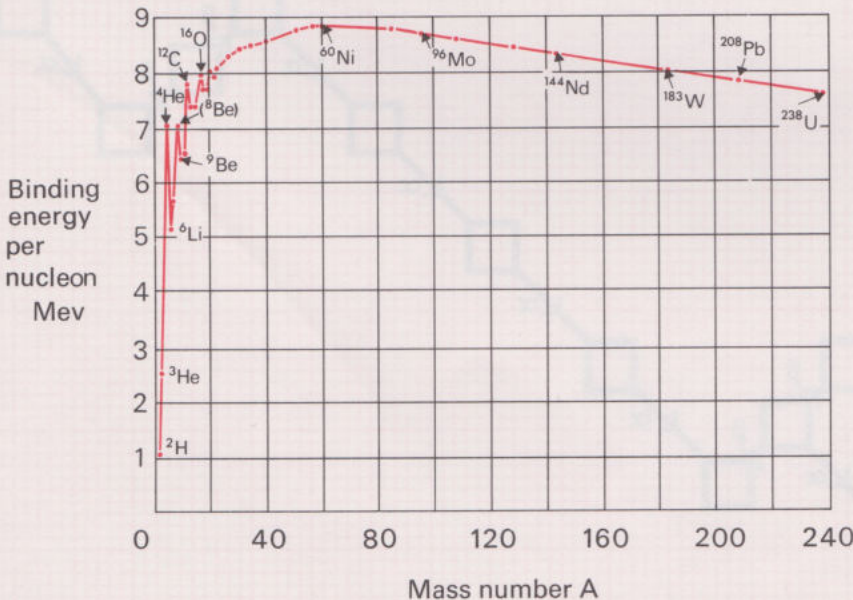


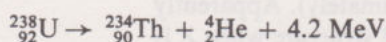
Figure 9 Binding energy per nucleon plotted against the atomic mass number A .

In the region of mass numbers above $A=56$, two new kinds of instability become important. (They are really two variants of the same process but

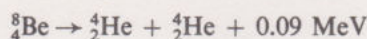
* If this puzzles you at all, think of it like this; remember that the more tightly bound the nucleon the lower is the energy level it occupies. The electrostatic repulsion between the protons makes them less tightly bound to each other and to the nucleus as a whole. So they occupy higher energy levels than the neutrons do.

it is usual to treat them as distinct. The second kind will be discussed in section 5.1.)

Experiments have shown that when $^{238}_{92}\text{U}$ decays to $^{234}_{90}\text{Th}$, 4.2 MeV of energy is released:



This is the first of the two important kinds of instability at high masses and is called α -decay because it involves the emission of an α -particle, or helium nucleus, ^4_2He . The energy is liberated because the mean binding energy per nucleon in the two lighter nuclei, $^{234}_{90}\text{Th}$ and ^4_2He , is greater than that in the heavier nucleus, $^{238}_{92}\text{U}$, that is, the nucleons are more strongly bound in the two lighter nuclei than they are in the heavier one. In other words, the 92 protons and the 146 neutrons in the $^{238}_{92}\text{U}$ nucleus have a greater total energy than the 90 protons and 144 neutrons in $^{234}_{90}\text{Th}$ and the 2 protons and 2 neutrons in ^4_2He . The difference is precisely 4.2 MeV. α -decay also happens to some unstable nuclei with low mass. For instance, ^8_4Be splits rapidly into two α -particles:



You may just about be able to see from Figure 9 that the mean binding energy per nucleon of ^4_2He is a little greater than the mean binding energy per nucleon of ^8_4Be .

The reason is that in ^4_2He all the nucleons are in the lowest possible energy level, which is full. In ^8_4Be , four of them have to go into the next level, which is much less tightly bound.*

On Figures 6 and 10 we can represent β^+ -, β^- - and α -decay as arrows which move across the Z-N plot. A β^+ -decay goes in this $\swarrow$ direction. A β^- -decay goes in this $\searrow$ direction. And an α -decay goes in this $\nwarrow$ direction.

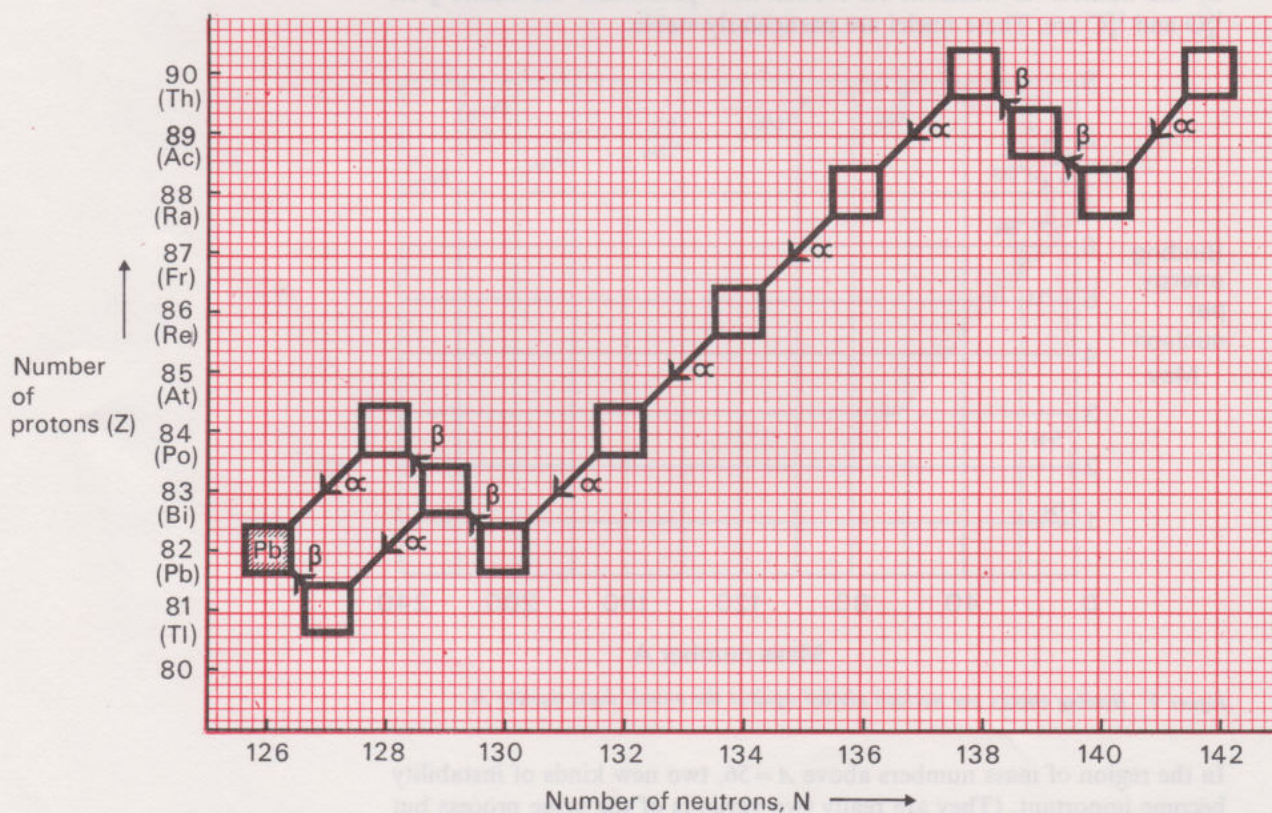


Figure 10 The thorium series.

* Remember, once again, that the lower the energy level occupied by a nucleon, the greater is its binding energy. The four neutrons and four protons in ^8_4Be between them have more energy than the four neutrons and four protons in the two helium nuclei ($^4_2\text{He} + ^4_2\text{He}$). Therefore the binding energy per nucleon in ^8_4Be is less than the binding energy per nucleon in ^4_2He . So ^8_4Be is unstable, and splits into two stable α -particles.

In Figure 10, you see that happens to a whole family of unstable nuclides called the 'thorium series'. This is one of four families to which all of the nuclei above $Z=82$ belong. None of the α , β^+ and β^- transitions within one of these decay series will make a *daughter nucleus** in one of the other series.

daughter nucleus

Why do you think this is?

β^+ - and β^- -decays do not change the value of the atomic mass number, A , and α -decay reduces A by 4 units. All the members of a particular decay series will therefore be connected by steps of zero or 4 in A . If the series starts at 238, then it will include nuclides with $A=234, 230, 226, 222$, etc.

Write down what you think the A values of members between 220 and 240 of the other three series will be.

The other series have 220, 224, 228, 232, 236, 240, or 221, 225, 229, 233, 237, or 223, 227, 231, 235, 239. These decay series are important in geology, since they occur in many minerals. The half-lives of α -decay processes, in particular, are often measured in thousands or even millions of years. Other decays, especially β^- -decays, may go very rapidly. In a particular mineral sample, it is frequently possible to find a significant amount of the parent nuclide of a series. The daughter nuclides all the way down to the stable end-product—usually a lead isotope—will also be present in quantities depending on their rate of production and decay.

What else might affect the abundance of daughter nuclides?

Some of the daughters will be gaseous—certainly the ${}^4_2\text{He}$ formed from α -particles. In certain series there are also isotopes of a gas called radon or radium-emanation with $Z=86$. This word 'emanation' gives the answer to the last question. Even when the mineral is solid, gaseous atoms may diffuse away from their point of production and escape. Thus, in a mineral sample, the abundance of daughters below radon in the series will depend on the ease with which radon has been able to escape from the sample. If you would like to know more about how α -decay takes place, turn to Appendix 1 (Black).

How are airships and North Sea gas connected with the properties of radioactive decays?

An answer to this question can be found in Appendix 3 (Black).

31.4.3 Summary of section 31.4

The total rest energy of a nucleus is measured by its mass. For a series of nuclides having the same value of atomic mass number A , the total rest energy is a minimum for some value of atomic number Z . This minimum determines the value(s) of Z for which the nucleus is stable. For light elements it occurs when Z is approximately equal to $\frac{1}{2}A$.

A nucleus which is not stable may decay to a stable nucleus by changing its value of Z in one of two ways. First, if Z is too small β^- -decay occurs. A neutron changes to a proton and a (negative) electron which is ejected from the nucleus. The nucleon moves to a vacant energy level in the

* A daughter nucleus is the nucleus that is left when a decay has taken place.

nucleus which is lower than its original energy before the decay. If, on the other hand, Z is too large, a proton changes to a neutron, and positron is ejected. This is β^+ -decay.

Secondly, heavy elements such as uranium may decay by the emission of a helium nucleus (called an alpha-particle). Alpha-decays have much longer half-lives than beta-decays. They can take place when the total rest energy of the decay products (including the alpha-particle) is less than that of the original nucleus—in other words, when it is possible to increase the mean binding energy. The atomic mass number is reduced by 4 and the atomic number by 2 in an alpha-decay. A radioactive series consists of all the elements that are linked by alpha and beta radioactive decays. Among the heavy elements there are four such series.

Now turn to the *Self-Assessment Questions* and attempt numbers 5, 6 and 8 (pp. 50 to 51).

31.5 Power from Nuclei

31.5.1 Nuclear fission

This is the other important form of instability which turns heavy nuclei into more tightly-bound, lighter nuclei.

α -decay is really just a special case of *fission*, but it is such a special case that we have treated it separately. α -decay is the most important form of fission which happens spontaneously to the nuclides found in nature. Other forms of fission, the kind we actually refer to as 'nuclear fission', happen to certain heavy nuclei, especially when they have been excited in some way. It has been mentioned already that excited nuclei often emit γ radiation, but large nuclei frequently undergo fission instead.

Nuclei may be excited in a number of ways, but one of the most effective is when a nucleus captures a slow neutron. The most practically important process of fission, up to the present day, is caused by the capture of a slow neutron on uranium $^{235}_{92}\text{U}$. You will remember that neutrons can get right up close to nuclei without having very much kinetic energy.

fission

Why?

They are not repelled by the long-range electrical force which would repel a proton.

What is the result when $^{235}_{92}\text{U}$ captures a neutron?

Excited $^{236}_{92}\text{U}$.

The resulting excited nucleus is a very unstable structure which oscillates rapidly between different shapes.

At this stage, we can introduce a model of nuclear behaviour which is, at once, utterly simple and quite accurate for heavy nuclei—the *liquid-drop model*.

liquid-drop model

BEFORE READING ON, DO HOME EXPERIMENT 1.

You have seen how a large liquid drop needs very little disturbance to break it into pieces. A heavy nucleus has some properties similar to those of a liquid drop.

What do the forces inside liquids and large nuclei have in common?

Both are held together by a short-range force. The nucleons, or molecules, at one side cannot feel the binding force of the nucleons, or molecules, on the other side—they can only feel the binding force due to their near neighbours. In liquids this gives rise to an important effect known as *surface energy*. An elongated drop can find a more stable, lower energy state by breaking into two smaller drops. This gives a reduction in the

surface area compared with the elongated condition. A reduction in the surface area reduces the surface energy. Surface energy is generally thought of as a macroscopic, i.e. large scale, effect as opposed to effects that are peculiar to the sub-microscopic world of the atoms and molecules. Similar 'macroscopic' effects apply to large nuclei where over 200 nucleons are jostling together in a small volume. 'Macroscopic' is in quotation marks here because nuclear sizes are still extremely tiny. The important point is that the diameter of a heavy nucleus is ten times as large as the range of the nuclear force. The capture of a neutron by $^{235}_{92}\text{U}$ is sufficient to set up a vibration in the resulting $^{236}_{92}\text{U}$ which distorts the nucleus so much that it can pinch across the middle—just as a liquid drop does when it is extended. The nucleus even assists in its own destruction in a way that a liquid drop cannot.

Can you guess how?

The two parts of the nucleus, as they begin to break away, will feel a smaller and smaller short-range attraction for one another, (due to the strong interaction) just as the two halves of a liquid drop would feel a smaller intermolecular force. But the long-range electrical repulsion, due to the protons in each part, will continue both during and after fission. Liquid drops do not have this additional factor tending to split them up. A further discussion of the liquid-drop model and quantum theory can be found in Appendix 2 (Black).

In the Home Experiment you may have noticed a few tiny drops left as the elongated large drop pinched into a column and then into two medium-sized drops.

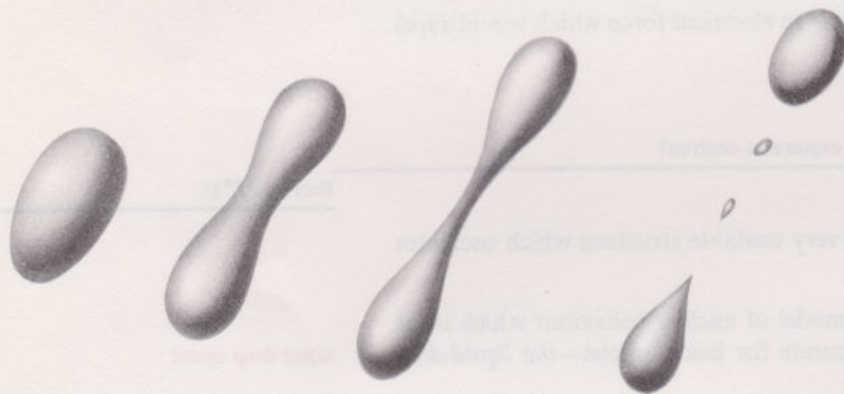


Figure 11 The disintegration of a liquid drop.

There is a nuclear analogy for these small drops too.

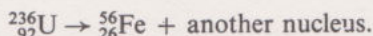
Can you guess what?

When nuclear fission occurs a few spare neutrons are produced in the fission process. Others are also emitted by the 'daughters' afterwards.

Why is it necessary for neutrons to be released?

You will remember from Figure 6 (c) that the heaviest nuclei are the ones with the largest proportional neutron excess. When two medium-sized

nuclei are produced by fission one of them might be a stable isotope—say we have for example,



What is the other nucleus?

If only two nuclei were produced, the other must be ${}_{66}^{180}\text{Dy}$. But the stable isotopes of ${}_{66}\text{Dy}$ have an atomic mass number A equal to about 162. There are 18 or so neutrons too many. Most of them are emitted from the daughter nuclides immediately as decay products, but some of them are delayed a short time. The other excess neutrons will change to protons with β^- -emission. Thus, after fission has taken place due to the capture of one neutron, many more neutrons will be released. Because of detailed differences in the properties of the different uranium isotopes, these neutrons are usually too energetic to give immediate capture on ${}_{92}^{235}\text{U}$, but they may capture on ${}_{92}^{238}\text{U}$ and induce a fission of ${}_{92}^{239}\text{U}$. With this build-up of neutrons, it is clear that one fission can lead to more than one subsequent fission. This self-perpetuating sequence of events is called a *chain reaction*. An electrical chain reaction occurs when the input microphone of an amplifier is placed in front of one of the output speakers. An inaudible noise will be picked up and amplified so that it is picked up again, louder and so on. This 'positive feedback' rapidly builds the noise up to a deafening howl. A nuclear chain reaction may begin if:

chain reaction

- there are enough heavy nuclei (a *critical mass*) packed close together, to catch one another's neutrons. (There must be some spontaneous neutron-producing processes to get things started. The α -particles from spontaneous decays will often interact with other heavy nuclei nearby, and sometimes knock out neutrons. Such neutrons and those from β^- - and γ -scattering are sufficient to start a chain reaction.)
- the neutrons have the correct energy to be captured readily on the heavy nuclei provided.

critical mass

What are the two major technological applications of chain reactions?

They are the nuclear bomb (the 'A-bomb') and nuclear electric power stations. In the former, a *critical mass* of ${}_{92}^{235}\text{U}$ (or a similar nuclide) is brought together and an uncontrolled chain reaction is set up. The temperature of the interacting uranium rises very rapidly due to ionization and atomic excitation, both by the energetic daughter nuclei and in turn by their decay products. This causes an explosion which is well known to be far more energetic and destructive than any chemical explosive. Vast quantities of fast neutrons are generated during the short time before the bomb disintegrates, and it is the fast neutrons which cause the chain reaction in this case. A large fraction of the uranium is involved in the fission process and used up. Something over 125 MeV is released per fission.

Calculate the energy release in joules when 235 grams of uranium ${}_{92}^{235}\text{U}$ is used up.

One way to appreciate the amount of energy involved in 1.2×10^{13} joules is to express it in terms of electrical energy. One watt is the power used when one joule of energy is consumed every second. A fair sized factory might use about 4 megawatt (4MW) so 1.2×10^{13} joules would keep it going for a month.

There are 6×10^{23} atoms of ${}_{92}^{235}\text{U}$ in 235 grams—one gram atom. If each of these gives up 125 MeV, there are $6 \times 125 \times 10^{23}$ MeV released, i.e. $6 \times 125 \times 10^{23} \times 1.6 \times 10^{-13}$ joules
 $= 1.2 \times 10^{13}$ joules

In nuclear reactors such as those used in the present generation of power stations, the property of $^{235}_{92}\text{U}$ to capture slow neutrons, with subsequent fission of $^{235}_{92}\text{U}$ is used.

Can you guess how the fast neutrons from one fission process can be slowed down enough to be captured by $^{235}_{92}\text{U}$ again?

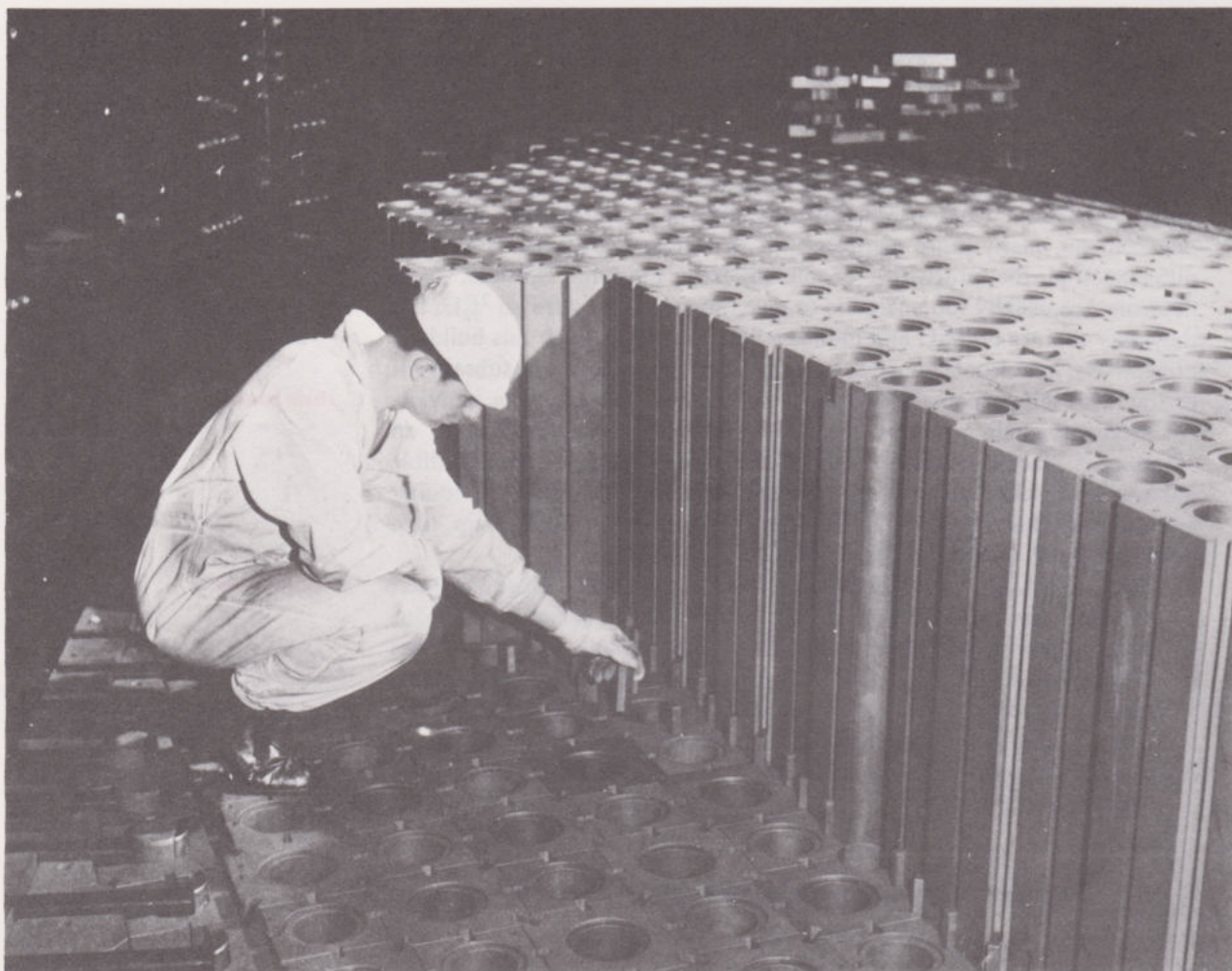


Figure 12 Laying the graphite core of a nuclear reactor.

Figure 12 is a photograph of the graphite blocks forming the core which houses the uranium-bearing fuel rods of a reactor in a power station. The most abundant isotope of carbon (graphite) is $^{12}_6\text{C}$, which has a particularly stable nucleus. This nucleus has no affinity for extra neutrons, so a high-energy neutron entering the graphite will tend to make a series of collisions with the carbon nuclei, giving up energy to them. The neutron is not absorbed, and in most cases it finally diffuses back with a suitably low energy into a fuel element.

The graphite, which slows down fast neutrons without absorbing them, is called a *moderator*.

moderator

How do you think the chain reaction can be controlled?

To control the chain reaction the number of free neutrons in the reactor core at any time must be kept constant. This is done by inserting *control rods* into the core. These contain nuclei with an affinity for neutrons. One such nucleus is boron $^{10}_5\text{B}$. When it captures a neutron it splits up, to form

control rods

the stable nuclei ${}^4_2\text{He}$ and ${}^7_3\text{Li}$, so the neutron is lost forever. The neutron flux is monitored continually. Whenever it rises above a predetermined level, the control rods are pushed a little further into the reactor. The extra neutron absorption reduces the number of neutrons and the chain reaction proceeds at a lower level. Fortunately, as mentioned earlier, some of the neutrons are only emitted from the daughter nuclides after a delay of a fraction of a second. This is vitally important because it gives time to move the control rods.

31.5.2 The costs of nuclear power

Since 1942, when Enrico Fermi first observed a chain reaction, the technology of nuclear reactors has been steadily refined and developed. In Britain and elsewhere tremendous resources have been made available for this research. As a result the Central Electricity Generating Board is now faced with a very even choice between oil-burning and nuclear power stations. Nuclear and oil-fired stations at present being built are expected to produce electricity at a little over 0.2p* per kilowatt hour.** The cost of distributing the electricity will however, always be greater than this.

The coal-fired stations which are due to start work in the next two or three years are expected to have a generating cost of 0.3p per kWh. The cost of nuclear power has come down significantly from around 0.4p per kWh in the past ten years, but is likely to be kept up near its present levels by a number of factors, some of them economic and technical, others of a social nature. The chief social factor is the need to ensure that the radioactive materials from a reactor are not released in dangerous quantities. Radioactive materials in the air, in water supplies or in the sea can cause grave damage to human life and to the balance of nature. The safety of the community and the environment must be considered at every stage of nuclear power station design. The need for rigorous safety precautions adds to the capital cost of nuclear power plants, which is somewhat higher than for conventional stations. A 1300 MW oil-fired station, which the CEGB is now planning (1970), will cost £80 million to build. A comparable 'Advanced-Gas-cooled Reactor' nuclear station will cost £100 million. (However, of this £100 million, something like £16 million will be the cost of the initial charge of fuel. This fuel will keep the station going for a considerable period. One of Britain's nuclear stations removed the last of its original fuel rods in 1970 after ten years of operation. Each ton of fuel can give about 3 000 MW-days of power.) The cost of fuel rods is also influenced by the need for safety. Most of the radioactive isotopes produced within the nuclear reactor are contained within the material of the rods. When a rod has been used it must be treated chemically to extract and separate the useful nuclides*** that have been generated from those that are not only useless but dangerous. The most dangerous, with radioactive half-lives of tens or hundreds of years, are embedded in glass or concrete and are buried in deep mines or dropped to the deepest part of the ocean bed. The failure of one of these containers could lead to a dangerous release of activity and it is difficult to be sure that this will not occur for hundreds of years. There is also a certain amount of radioactivity released directly into the atmosphere by nuclear power plants. However this is generally very small and it is fairly easy to keep a continuous close watch on the amount of this contamination and shut down the reactor in the case of an unexpected increase. Despite these problems it is

* Costs in this section are based on data from the Central Electricity Generating Board, November, 1970.

** 1 kilowatt-hour (kWh) = 3.6×10^6 joule.

*** The benefits to medicine and industry from artificial radioactive substances are many and varied, but are beyond the scope of this Unit to describe.

expected that nuclear power plants will continue to show increasingly favourable generating costs, compared with conventional stations, largely because the cost of conventional ('fossil') fuels is bound to increase in the next few decades as they get scarcer. This trend is now seen in the U.S.A. and elsewhere, as well as in Britain.

31.5.3 Another source of nuclear power—fusion*

Take another look at Figure 9 (p. 25). You will remember that fission processes involve moving from the extreme right of the curve, up the slope towards the broad region of tightly-bound nuclei around ${}^{56}_{26}\text{Fe}$.

Where else would it be possible to move up a slope on this curve? What kind of processes would achieve such a movement?

Clearly there is a slope to move up on the left of the graph too. This would involve building up complex nuclei from simple ones with low values of the atomic mass number A . But we know that nuclei have positive charge, so nuclei which are close together repel one another. It is therefore difficult to push a pair of low mass nuclei very close to one another.

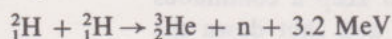
Why do they need to be very close to one another if they are to coalesce?

The short range of the strong interaction means that the two nuclei must be only around 10^{-15} m apart before they will attract one another. Kinetic energy is needed to bring the two nuclei this close together. This energy can be acquired in one of two ways. The first way is to take individual nuclei and accelerate them one by one. This is an important technique, but the number of nuclei that can be accelerated at once is too small for it to be useful in this context.

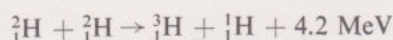
How else can nuclei be given very high energies?

The other way to give energy to nuclei is to raise the material containing them to a very high temperature. In Unit 5 you saw that hot material contains atoms and molecules with large kinetic energies. If the temperature is raised to above 10^6 K, then there will be some nuclear collisions with enough energy to overcome the effects of electrical repulsion. The nuclei will sometimes approach closely enough to feel one another's strong attraction, and *fusion* may take place.

The only artificial fusion process so far achieved is in the 'H-bomb'. In the early versions, a uranium fission bomb was used to achieve a very high temperature. A jacket of light elements around the A-bomb is heated to sufficiently high energies for fusion to occur. Several processes could be used of which the simplest are:



or, with equal probability,



i.e. deuterium (heavy hydrogen) is built up to an isotope of helium plus a neutron, with the release of 3.2 MeV. Alternatively tritium, the heaviest

* A useful book that you might like to refer to if you wish to follow up this subject is: H. R. Hulme, Nuclear Fusion, Wykeham, 1970.

hydrogen isotope, is produced with a proton and 4.2 MeV kinetic energy.

A deuterium-tritium reaction occurs at lower temperatures, but tritium is very expensive.

However, fusion processes are ultimately the source of all available energy on the Earth, in that they produce stellar energy. The centre of a star, such as a star as the Sun for instance, contains compressed material at a very high temperature. If the temperature were not so high, it could not support the enormous mass of material piled on top of it. Remember the pressure in a gas depends on the temperature. At the centre of the Sun the material forms a very hot gas called a *plasma*. In a plasma there are very few neutral atoms. The individual kinetic energies of the atoms are much higher than the binding energies of many of their electrons. Whenever there is a collision between two such atoms, they tend to lose their electrons. A plasma contains lots of such free electrons, and atoms in the form of positive ions. They are all moving with very high velocities and undergoing repeated collisions with one another—electrons with electrons, electrons with ions, and ions with ions. If atoms have been completely stripped of their electrons by earlier collisions, then an ion-ion collision is really a collision between two bare nuclei.

How will such a situation give rise to fusion processes?

In exactly the same way as in the H-bomb—which produces a plasma when it is detonated. It is known that the Sun is largely composed of hydrogen, with some other light elements, but very small quantities of heavy elements. In the core of the Sun, the products of a particular nuclear encounter are not carried away rapidly from the highest temperature region. This region is very large—thousands of kilometres across. If a certain nuclide is produced in one encounter, it may, at a later time, take part in another. There can therefore be a number of other fusion processes as well as the one-step processes, such as the two examples we gave for possible ‘H-bomb’ reactions.

One sequence of reactions which is thought to occur in the Sun is shown in Figure 13.

This, and other, ‘hydrogen-burning’ processes provide the source for the enormous amounts of solar energy which are radiated to us and into space. These fusion processes only occur in the centre of the Sun. A whole sequence of heat-transport mechanisms carries the energy up to the surface regions before it is radiated to us as visible light.

Attempts have been made to build apparatus in which controlled fusion processes will occur. So far they have not been successful because our techniques for containing very hot plasmas are not good enough.

Why cannot plasmas be contained in ordinary steel retorts?

If a plasma touches a solid object, the solid is vaporized by the high temperature of the plasma, and the plasma itself cools down rapidly. So it is necessary to invent some other means of restraining the movement of the plasma; this is provided by a suitable arrangement of magnetic fields. We saw just now that a plasma is composed of charged particles, positive ions and electrons—all moving at high speeds. A fast moving charged

plasma

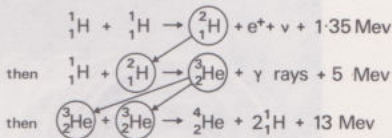


Figure 13 A sequence of possible fusion reactions inside the Sun.

particle is in itself an electric current. But electric currents are deflected sideways by magnetic fields.

Where do you apply this principle in everyday life?

Such deflection of electric currents by magnetic fields is the basis of the operation of electric motors in anything from hair dryers to tube-trains and of the usual kind of loudspeaker. As you saw in the TV programme of Unit 6 this effect can be demonstrated by putting a magnet close to the screen of a television set. *Do not do this if you have colour TV.* As the electrons in the tube approach the screen, they are deflected by the magnetic field close to the magnet.

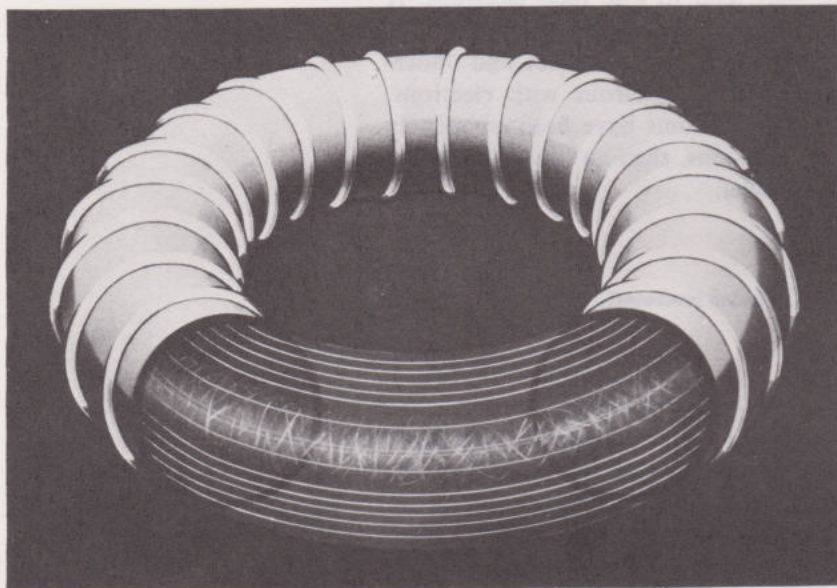
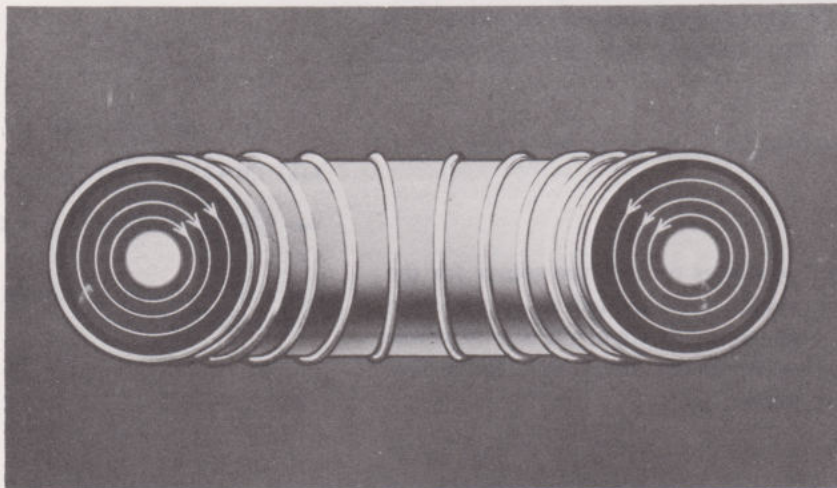


Figure 14

(a) A magnetic means of containing a plasma.



(b) Showing the secondary magnetic field in the 'plasma bottle'.

One lay-out of magnetic field that has been used as a magnetic bottle for plasma is shown in Figures 14 (a) and 14 (b). The doughnut-shaped field forms a 'bottle' that has no end. Charged particles in the plasma might start off in an outward direction from the ring, but they deflect sideways around the field direction and cannot get away. The curved lines on Figure 14 (a), running across the cut-away part of the tube, represent the direction of the magnetic field. The tangle of fine lines at the core of the tube represents the plasma of ions spiralling around the field lines. Figure 14 (b) shows the secondary magnetic field produced when a current is induced in the plasma. This secondary field pinches the plasma in towards the core of the tube. The induced current both heats the plasma and causes it to pinch away from the walls of the bottle. If high enough temperatures

could be attained for long enough, the fusion process itself would heat the plasma, producing a fusion chain reaction.

The trouble with making a long-lasting bottle of hot plasma is that the plasma wanders away from its proper place and hits the walls of the containing vessel. So far, all attempts to contain plasma have worked for too short a time for the temperatures to be raised to the level required for fusion to begin.

Research on this problem has been pursued vigorously throughout the last decade, but success is coming very slowly. If fusion processes could be made to occur in a controlled way, and if a way could be found to convert the energy produced into heat, the world would have a new energy source with nearly unlimited supplies of fuel.

Where is this fuel?

Controlled fusion processes will probably use deuterium as a fuel and possibly hydrogen or lithium. The seas contain sufficient of these to satisfy all our foreseeable energy requirements. This is in sharp contrast to world supplies of oil and coal. At the expected rate of consumption, based on current trends, world reserves of these fossil fuels could be exhausted within one hundred years. The long-term situation is more serious, because oil and coal form a unique reserve of organic chemical raw materials. A substantial amount of them must be held for these purposes, and not simply burnt.

31.5.4 Summary of section 31.5

Large nuclei such as uranium 235 can be made to capture an extra neutron and then break into two fragments of smaller size. This process is called nuclear fission and is in principle similar to alpha-decay. It can occur when the total rest energy of all the fragments is less than that of the original nucleus—uranium 236 in this case. The breaking of a liquid drop into two smaller drops is a useful model of the fission process (the liquid-drop model). Nuclear fission releases large amounts of energy and is the basis of nuclear power stations and the atom bomb. Neutrons released from a fission are captured and cause further fissions. If at least one neutron from each fission goes on to produce a further fission, a chain reaction may take place which is uncontrolled in an atom bomb but controlled in a nuclear power station. The control is by neutron-absorbing control rods which are withdrawn from the reactor core just far enough to allow a chain reaction to develop; the core also contains a moderator to slow down the neutrons so that they can be captured more easily by the uranium. Nuclear stations can produce electricity appreciably more cheaply than modern coal-fired stations. Rigorous precautions are necessary in nuclear power stations to prevent the escape of radioactive material into the surrounding area. This is discussed further in Unit 34.

Energy can also be released when two light nuclei such as hydrogen are fused together—nuclear fusion. This process requires very high temperatures and is the basis of the hydrogen (H) bomb. Such temperatures are also found inside stars such as the Sun; fusion is the source of the energy for the Sun's radiation. Attempts to control a fusion reaction for use in power stations by confining a plasma in a magnetic field have so far been unsuccessful.

Now turn to pp. 50–1 and attempt the remaining Self-Assessment Questions, 4, 7, 9 and 12.

Summary of the Unit

The nucleus of an atom has a diameter of a few femtometres—some 10^5 times smaller than the atom itself. This diameter can be measured by scattering a beam of high momentum particles, such as electrons, from the nuclei and analysing the distribution of scattered particles. The nucleus is held together by a force called the 'strong interaction' having a very short range—about 2 femtometres. The values of the binding energy of the first nucleon in various nuclei indicate an energy-level structure for the nucleons, analogous to the energy levels of atomic electrons. Further evidence about nuclear structure is obtained from nuclear spectroscopy, in which the wavelengths of gamma-rays (photons of very short wavelength) from excited nuclei are measured. Two separate energy-level structures (shell structures) are indicated, one for the protons and one for the neutrons. For a given atomic mass, only a very few nuclides are stable; for lighter elements, the numbers of neutrons and protons are about equal, but heavier elements have a neutron excess. A nucleus with the wrong relative number of neutrons and protons is unstable; it becomes stable by radioactive decay, converting protons to neutrons by β^+ -decay or neutrons to protons by β^- -decay. Alternatively some nuclei, especially among the heavy elements, undergo α -decay. This is a special case of nuclear fission. In other fission processes, a heavy nucleus breaks up into two smaller pieces, usually of unequal but comparable sizes. When fission occurs, considerable amounts of energy are released in the form of kinetic energy of the fragments. A self-perpetuating chain-reaction can occur, which is either uncontrolled (A-bomb) or controlled (nuclear electric power station). Nuclear power stations are likely to produce a large proportion of the world's electricity in the foreseeable future. Energy is also released by the fusion of light elements such as hydrogen. Fusion occurs in stars and the 'H-bomb'; research aimed at controlling a fusion reaction to generate power steadily and continuously has so far only been partially successful, but success in this would probably satisfy all foreseeable energy needs of the world.

Appendix 1 (Black)

Tunnelling—how quantum theory affects α -decay

What do ${}^8_4\text{Be}$, ${}^{12}_6\text{C}$, ${}^{16}_8\text{O}$, and ${}^{20}_{10}\text{Ne}$ have in common?

Each of these nuclei has in it two, three, four or five times the number of neutrons and protons that there are in ${}^4_2\text{He}$. The nuclei ${}^{12}_6\text{C}$, ${}^{16}_8\text{O}$, and ${}^{20}_{10}\text{Ne}$ often behave like three, four or five α -particles bound together. We have already mentioned that ${}^8_4\text{Be}$ very rapidly becomes two α -particles.

Why do you think these nuclei behave like composites of α -particles?

The reason is simple. The α -particle is a very stable, and relatively small, structure. Inside a large nucleus, nucleons tend to pack together in the snuggest possible way. One way in which they might achieve this is if they combine in the form of α -particles inside the larger nuclear structure. There is experimental evidence that such α -particles do exist in nuclei, at least near the surface.

You may have some difficulty at this point switching from one model of the nucleus to what is essentially another. Up to now we have taken the atomic energy-level structure as our model for what is going on inside the nucleus—and a very successful model it is too. But like all models and analogies they must not be pressed too far. There are differences between the forces acting on electrons in an atom and the forces acting on the nucleons inside a nucleus. In an atom there is a well-defined centre of attraction (the nucleus); in the nucleus itself, because of the short range of the strong interaction, there is no well-defined centre of attraction for the nucleons. We could therefore expect nucleons to show some tendency to form compact localized clusters (α -particles). When one comes across a phenomenon that is extremely closely related to this particular behaviour of nucleons, it is fruitless to try and describe it using a model not adapted to that kind of situation. It is best to change to another mental picture—one in which the nucleus is regarded for at least some of the time as being made up of α -particles in motion rather than individual nucleons in motion.

Some heavy nuclei emit α -particles in order to achieve a more stable arrangement of their constituents. If one wishes to understand α -decay on a deeper level, it helps to use this picture of α -particles already existing inside the heavy nucleus before the decay happens.

Look back to section 31.4.2. What is the binding energy of the first α -particle in ${}^{238}_{92}\text{U}$?

Apparently this must have a negative binding energy! You would have to give an α -particle 4.2 MeV to get it into ${}^{234}_{90}\text{Th}$ nucleus, to make ${}^{238}_{92}\text{U}$. Binding energy is defined as the energy needed to get a particle out of a nucleus.

Clearly this is why ${}^{238}_{92}\text{U}$ decays into $\alpha + {}^{234}_{90}\text{Th}$, but it takes a very long time to do it. Its half-life is 4.51×10^9 years. So one can picture the α -particle trying for something like four and a half thousand million years before it

is permitted to do something which it might be expected to do immediately; that is, to jump out and get away with 4.2 MeV of kinetic energy.

To understand what causes the delay one needs to use a little quantum theory, and to introduce the concept of a *potential distribution*.

NOW DO HOME EXPERIMENT 2 (BLACK). THIS WILL SHOW YOU THAT A POTENTIAL DISTRIBUTION IS QUITE AN EASY THING TO PICTURE.

What does the decay α -particle in ${}_{92}^{238}\text{U}$ have in common with a marble on an upturned plate?

Quite a lot, since both have an excess of potential energy. When either particle 'escapes' from its system, this excess of potential energy appears as kinetic energy. Once the particle leaves the nucleus it does so with 4.2 MeV of kinetic energy. Similarly, if one nudges the marble on to the slope of the rim it will run off across the carpet.

But the potential distribution for the α -particle is a more complicated shape than shown in Figure 3 in Home Experiment 2. Within a few fm of the centre of the nucleus the α -particle will feel a strong attractive force.

Let us try to build up a picture of the potential experienced by an α -particle in the region of a heavy nucleus. For a start, the charge on the nucleus is not all concentrated at one point, so the electrostatic part of the potential does not look like Figure 3.

Sketch the electrostatic potential distribution you expect near and within a large nucleus.

Your sketch should look like Figure 15.

Because the charge on the protons is distributed throughout the volume of the nucleus, there is no sharp increase in the potential when $r \approx 0$ at the very centre.

In 31.3.1, you learned that a nucleon deep inside a heavy nucleus is acted upon by all the surrounding nucleons in a balanced way, but at the edge of the nucleus (Figure 2, p. 14) a nucleon will be attracted inwards by the strong interaction of its neighbours. An α -particle is made up of nucleons, so it would also be attracted inwards when it is near the nuclear edge.

Sketch the strong interaction potential distribution you expect for a nucleon or α -particle near or within a large nucleus.

Your sketch should look like Figure 16.

Notice that this is approximately a 'square well' potential. The similarity with a hole in a putting green is not fortuitous. A particle remote from the nucleus feels no force—there is no slope to the potential. A particle deep inside the nucleus feels no force, just as the golf-ball may lie anywhere at the bottom of the hole. But the steep sides have an inward slope which corresponds to a strong inward force on a particle at about 5 fm from the centre, like a ball running down into the steep-sided hole.

An α -particle experiences both electrostatic and strong forces.

Sketch the shape that you would expect the effective combined potential to have for an α -particle in or near a large nucleus.

Figure 17 gives the shape you should have sketched.

You will notice that the strong interaction potential dominates the potential within the nucleus. The electrical potential dominates outside.

At point A it is in the middle of the potential well, so its potential energy, U , is -10 MeV. Its kinetic energy, T , must therefore be $+8$ MeV so that $U + T = -2 = E$, the energy of the level (notice that $-E$ is the same as the binding energy of the α -particle).

At point B, the potential energy, U , is -2 MeV, so the kinetic energy T , is zero. One can compare the motion of the α -particle inside the potential well to a marble rolling around *inside* a plate *right way up*. The highest point the marble can reach on the rim of the plate is the point at which all of its kinetic (rolling) energy has been turned into potential energy (height). When it runs back onto the bottom of the plate, it gets the kinetic energy back again.

If Figure 17 represents the potential distribution for α -particles in $^{238}_{92}\text{U}$, draw in the energy level for the α -particle which waits 4.51×10^8 years or so before escaping.

When you have done this (and *not* before), check your energy level with Figure 18 on p. 43.

On Figure 18 you see what you should have drawn. Notice that the level energy in this case is 4.2 MeV above zero.

What seems to be stopping the α -particle from getting out?

The α -particle cannot get out because there is a potential hill between the nucleus and the outside world. The downward slope runs inwards on the inside of this hill.

Why is the downward slope directed inwards on the side of the potential hill that is closer to the centre of the nucleus?

An inward slope denotes an inward force. The strong attraction of the nuclear force pulls the α -particle back when it tries to leave the edge of the nucleus. This strong attraction dominates the electrical repulsion at the inside edge of the barrier region.

In Figure 2 (p. 14) you saw how a nucleon at the edge can feel an attractive force, since all the other nucleons are attracting it from one side only. The same is true for an α -particle which tries to leave the edge of the nucleus. This is what the inward slope of the potential distribution represents.

Why is the slope directed outwards on the side of the potential hill that is further from the centre of the nucleus?

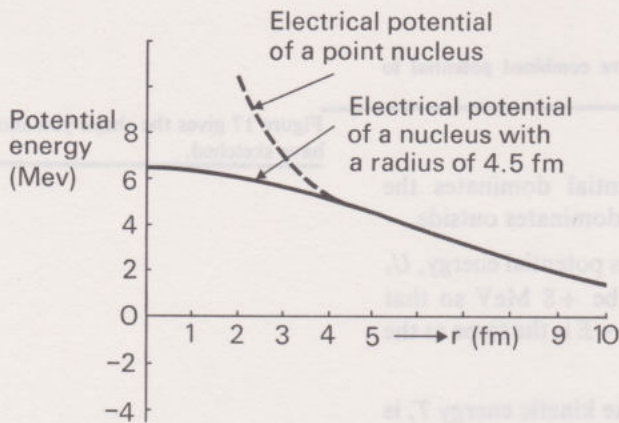


Figure 15 Electrical potentials of a point-nucleus and of a large nucleus.

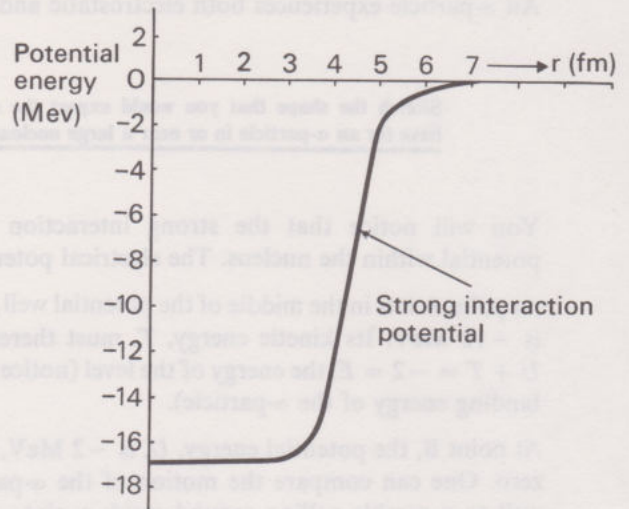


Figure 16 Strong interaction potential for an α -particle due to a large nucleus.

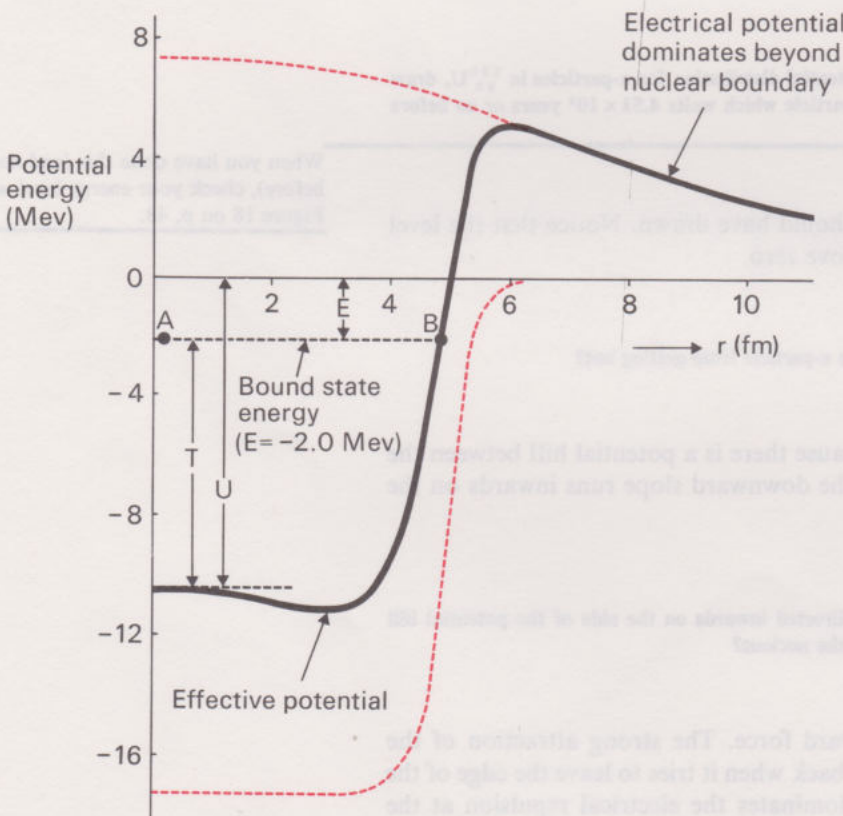


Figure 17 Effective potential for an α -particle in and near a large nucleus.

Once the α -particle has left the short range of the strong interaction, it feels only the electrical repulsion.

So now one can see what the problem is. In terms of 'common sense' physics, there is no way in which an α -particle can jump over the potential hill and get out. It is like a zoo. The animals are often kept in cages with open tops and high slippery sides. If a lion got out of its cage, then it

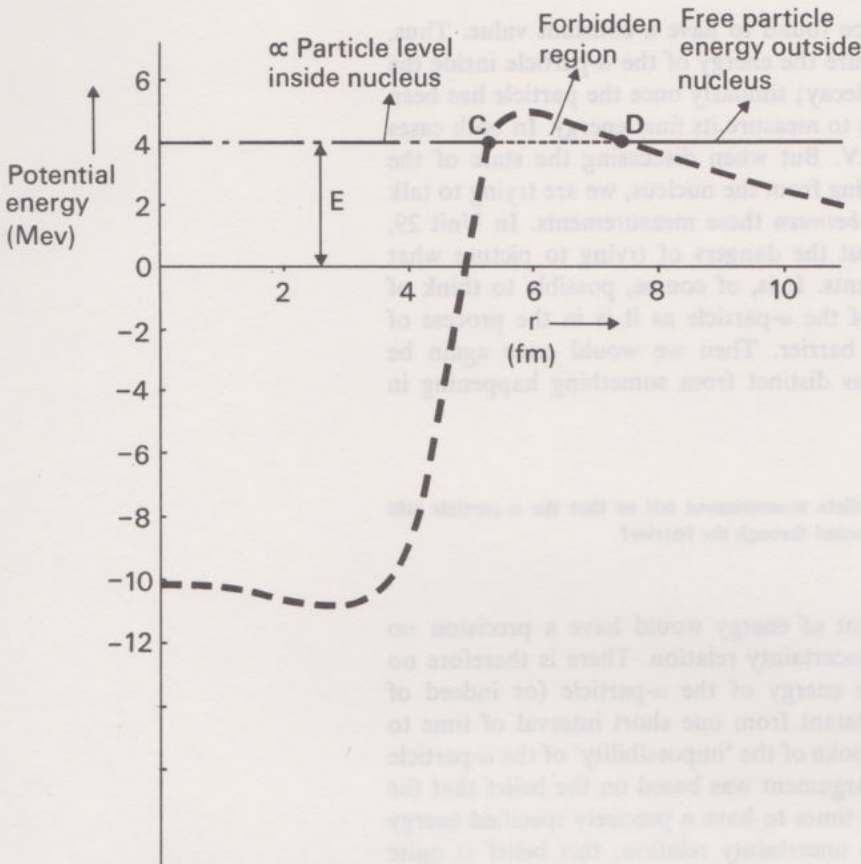


Figure 18 The potential barrier for an α -particle.

would be free to run off and go anywhere it chose. But a lion cannot spring over the side of its cage. It can never have sufficient kinetic energy to get over the potential hill of the cage side. α -decay of $^{238}_{92}\text{U}$ appears just as impossible as a lion jumping a twenty-foot wall, but it happens. The question is not 'What delays the α -particle from being emitted?', which is the problem faced earlier in this section, but rather 'How is it possible for the α -particle to be emitted at all?!'

The reason has to do with Heisenberg's uncertainty principle.

How can the uncertainty principle help?

As you saw in Unit 29 there is an uncertainty relation that can be expressed mathematically as $\Delta E \cdot \Delta t \approx h$. That is, during a short time Δt , we cannot be sure of the energy of a particle to better than some precision ΔE , where $\Delta t \approx h/\Delta E$. Now the whole trouble with getting over the potential hill is that, in the region from point C to point D of Figure 13, the value of the potential energy U is greater than the level energy E . If a particle is to get out of the nucleus therefore, it must somehow increase its energy for a short time—the time required to get from C to D.

Is there anything to stop it having a fluctuation in energy?

The law of conservation of energy says that if a long period is available for measuring the energy of a system, then successive readings each taken

over long periods of time will be found to have a constant value. Thus, we can take our time and measure the energy of the α -particle inside the nucleus very precisely prior to decay; similarly once the particle has been emitted we can take a long time to measure its final energy. In both cases the answer is precisely 4.2 MeV. But when discussing the state of the α -particle as it is actually emerging from the nucleus, we are trying to talk about something that happens *between* these measurements. In Unit 29, you were strongly warned about the dangers of trying to picture what happens in between measurements. It is, of course, possible to think of trying to measure the energy of the α -particle as it is in the process of passing through the potential barrier. Then we would once again be talking about a measurement as distinct from something happening in between measurements.

But would such an intermediate measurement tell us that the α -particle still had energy 4.2 MeV as it passed through the barrier?

Probably not. This measurement of energy would have a precision no better than that given by the uncertainty relation. There is therefore no experimental evidence that the energy of the α -particle (or indeed of anything else) must remain constant from one short interval of time to the next. But earlier, when we spoke of the 'impossibility' of the α -particle getting out of the nucleus, the argument was based on the belief that the energy of the particle had at all times to have a precisely specified energy of 4.2 MeV. According to the uncertainty relation, this belief is quite unjustified. There is nothing in fact to stop us using theoretical models in which the α -particle is considered capable of 'borrowing' an energy ΔE for a time Δt given by the uncertainty relation.

Unfortunately for the α -particle, the rather large amount of energy ΔE needed means that its chance of getting out in the time Δt is very small indeed. But it keeps on trying, and after 4.51×10^9 years there is a 50–50 chance that it will have succeeded.

Do you expect that the chances of the α -particle getting out of a particular nucleus will change with time?

You saw in Unit 6, section 6.3, that there is no change of the decay probability with time. In a sample of $^{238}_{92}\text{U}$, or any other of the nuclides listed in Unit 6, the rate of α -emission of the sample depends on

What?

It depends upon the kind of nuclide, in particular its half-life, and the amount of it present in the sample.

The process by which an α -particle escapes from a potential well, through a region of high potential, is called *tunnelling*. Such tunnelling through *potential barriers* occurs in other contexts in nuclear physics, and in semiconductor devices used in electronics.

tunnelling
potential barriers

Appendix 2 (Black)

The liquid-drop model and quantum tunnelling

In a detailed calculation of the speed of a fission process, using the liquid-drop model, physicists must also consider quantum tunnelling effects. The excited $^{236}_{92}\text{U}$ nucleus sits there shaking for a while like a wobbling liquid drop, after the slow neutron has been absorbed. But the strong nuclear force causes a potential barrier against break-up in this case, just as we saw it did in α -decay. To pinch across the middle and break, the nucleus needs to borrow a little energy for a short time. In this case, the energy involved is small enough that the process can go ahead very rapidly—fast enough to beat the alternative way that the excited nucleus can lose energy, by γ -ray emission. It doesn't have to wait millions of years.

Do you expect quantum tunnelling effects to be significant in the break-up of real liquid drops?

The value of h is so small that in the macroscopic world we rarely notice quantum effects. $h = \Delta E \Delta t = 4.0 \times 10^{-21}$ MeVs. This is quite a big number on the nuclear level where 4.0 MeV is a typical binding energy and things often happen in 10^{-21} second. In macroscopic units, $h \approx 10^{-34}$ Js. The surface energy of a small drop of water might change by 10^{-5} joule when it is split up. But in 10^{-29} second the two parts could not get very far apart!

Airships and alpha-particles

The Zeppelins and other airships from the First World War, until the 1930s, were filled with hydrogen gas. With only thin canvas between the hydrogen and the air, the danger of fire was enormous. In fact, disastrous fires wrecked many of the largest airships. None have been used commercially since the mid-30s for that reason.

What other gas could be used to fill a lighter-than-air balloon?

Already in the 1930s it was known that helium gas would be a non-inflammable substitute for hydrogen in airships. Unfortunately, helium is expensive and there are very few sources of pure helium. This may seem strange, since the helium nucleus is so stable, and there are so many α -emitting nuclei in the world. In fact, its great stability means that ${}^4_2\text{He}$ is the second most abundant nuclide in the whole universe. Why then is there so little of it available on Earth?

The answer lies in two other properties of helium—its low chemical affinity for other atoms and its lightness. Since helium has closed electron shells, it does not bind very readily into compounds. It prefers to float free as a gas, and since it is lighter than air, it floats right to the top of the Earth's atmosphere. The gas at the top of the atmosphere is exposed to the full radiation of the Sun. This heats it to high temperatures and molecules of a high temperature gas have high kinetic energies (see Unit 5, section 5.2.3). For helium the kinetic energies involved correspond to such high velocities that individual molecules can completely escape from the Earth's gravitational attraction and drift off into space. This was discussed in Unit 27.

Why do the Earth's hydrogen, oxygen and nitrogen not diffuse away in the same way?

In fact hydrogen does, but so much of it is bound up chemically in water that we will never run out of it. Oxygen ${}^{16}_8\text{O}$ and nitrogen ${}^{14}_7\text{N}$ both are heavier than helium ${}^4_2\text{He}$, and they form diatomic molecules, while helium is monatomic. This means that O_2 molecules are approximately $2 \times 16/4 = 8$ times as heavy as He.

N_2 molecules are how many times heavier than He?

Approximately,

$$\frac{2 \times 14}{4} = 7 \text{ times heavier than He.}$$

The temperature of the upper atmosphere determines the range of values of the kinetic energy T of the gas molecules. The velocity of one such molecule is then found from equation 25 of Unit 4, section 4.4.4:

$$\begin{aligned} T &= \frac{1}{2} mv^2 \\ \therefore v^2 &= \frac{2T}{m} \\ \text{so } v &\propto m^{-\frac{1}{2}} \end{aligned}$$

At a given temperature, the range of kinetic energies is the same for all molecules whatever the value of m .

What is the ratio of velocities between an oxygen molecule and a helium atom if both have the same kinetic energy?

The mass of an atom of helium is approximately 4 units and of a molecule of oxygen 32 units, so the ratio of masses is about 8:1. Hence the ratio of velocities is $1:\sqrt{8}$ or 1:2.8. An oxygen molecule moves more slowly than a helium atom by this factor. For nitrogen the ratio would be 1:2.7.

This difference in velocities is enough to allow the Earth's gravity to hang on to our oxygen and nitrogen, though our free helium can escape. So where does North Sea gas come in?

North Sea gas comes out of the ground. It has been there for a long time, gradually collecting under an impervious layer of rock. Among the minerals under that rock are some containing members of the radioactive series. Each α -particle from a decay captures two electrons and becomes an atom of helium. Some helium diffuses out of the material in which it was formed and collects with the petroleum gas under the impervious layer of rock. When the gas is released the helium comes with it. This helium can be extracted by commercially viable processes, so it is now possible to think realistically of filling commercial airships with helium. However, even the natural gas sources may begin to run out within a few generations.

Artificial nuclear reactions give off α -particles and it is amusing to see whether a nuclear-powered airship could make its own helium.

If such an airship is powered by a process that gives an α -particle as a by-product for every 6.125 MeV of energy produced, calculate the rate at which it can make up its own helium supply. Assume its motor generates one megawatt of power.

(Assume 1 MeV = 1.6×10^{-13} joule)

One megawatt is 10^6 joules per second

$$= \frac{10^6}{1.6 \times 10^{-13}} \text{ MeV per second}$$

The number of particles per second will be:

$$\frac{10^{19}}{6.125 \times 1.6} = 10^{18}$$

One mole of helium contains roughly 6×10^{23} α -particles (Avogadro's number). One mole of a gas at standard temperature and pressure occupies

22.415 litres, say 20 litres. Hence, in one second *approximately* $\frac{20 \times 10^{18}}{6 \times 10^{23}}$

litre of helium are produced.

In one hour about $\frac{60 \times 60 \times 20}{6 \times 10^5} = 0.012$ litre of helium are produced.

This is not enough to make up for the leakage, by diffusion, of helium from the enormous balloon.

Glossary

CHAIN REACTION A fission reaction initiated by a neutron, and in which sufficient neutrons are given out for the reaction to be self propagating.

CHARGE INDEPENDENCE An interaction whose strength does not depend on the charge of the particles involved. This is an important property of the strong interaction.

CONTROL ROD Rod made of a material which strongly absorbs neutrons. By varying its position in a reactor, the power level can be controlled.

CRITICAL MASS The minimum mass of a given fissile material in which a chain reaction can occur.

EFFECTIVE NUCLEAR RADIUS The radius of the nucleus as deduced from a particular experiment. Different types of experiments measure slightly different radii.

LIQUID-DROP MODEL The analogy of fission with the break-up of a drop of liquid when disturbed.

MEAN BINDING ENERGY PER NUCLEON The total energy needed to take a nucleus apart, divided by the number of nucleons.

MODERATOR Material placed between fuel elements in a reactor to slow neutrons down without appreciable absorption.

NEUTRON EXCESS The difference between the number of neutrons in a nucleus and the number of protons.

NUCLEAR FISSION The splitting of a nucleus (usually a heavy nucleus) into two fragments of approximately half the size of the original nucleus, with the release of energy.

NUCLEAR FUSION The formation of a stable nucleus by the addition of two lighter nuclei.

NUCLEON A proton or a neutron (or their antiparticles).

NUCLEON DENSITY The number of nucleons per fm^3 .

NUCLEON ENERGY LEVEL One of the discrete series of allowed energies for a nucleon in a nucleus.

POSITRON The positive counterpart (antiparticle) of the negative electron.

RADIOACTIVE SERIES A series of unstable nuclei linked by α -decay.

STRONG INTERACTION The dominant attractive interaction between nucleons at distances less than 1 fm.

TOTAL NUCLEAR BINDING ENERGY The total energy needed to take a nucleus apart.

Self-Assessment Questions

Question 1 (Objective 2)

Choose the correct alternative in each of the following statements.

- (a) The radii of most nuclei are a few times $10^{-17}/10^{-15}/10^{-12}$ m.
- (b) The radii of nuclei are much less/the same/much more than the range of the strong interaction.
- (c) Every known nucleus has a radius of more than $10^{-14}/10^{-16}/10^{-18}$ m.
- (d) A nucleon in a large nucleus feels the strong attraction of one/a few/all of the other nucleons.

Question 2 (Objective 3)

The first diffraction minimum for the scattering of neutrons from zinc $^{64}_{30}\text{Zn}$ falls at 30° . The effective-radius of the zinc nucleus is given by

$$r = 1.2 A^{1/3} \text{ fm.}$$

Calculate the approximate momentum of the neutron beam ($\hbar = 6.6 \times 10^{-34}$ J s).

Question 3 (Objective 1)

Decide which of the following statements is a suitable definition of the following terms.

- A Mean binding energy per nucleon.
 - B Neutron excess.
 - C Nuclear energy level.
 - D Excited nucleus.
- 1 A situation in which β^- -decay is bound to happen.
 - 2 An energy at which neutrons, or protons, may exist inside a nucleus.
 - 3 The energy of the neutrons, or protons, in a nucleon beam.
 - 4 A nucleus which is not in its ground state.
 - 5 The nucleus of an ionized atom.
 - 6 The difference between the number of neutrons N , in a nucleus, and the atomic mass number A .
 - 7 The energy required to remove all of the nucleons from the nucleus, one by one.
 - 8 The mass defect of the nucleus, expressed in MeV/c^2 .
 - 9 A situation in which there are more neutrons than protons in a nucleus.
 - 10 The difference between the number of neutrons N , in a nucleus, and the atomic mass number A .
 - 11 The energy required to break up the nucleus into its constituent nucleons, divided by atomic mass number A .
 - 12 A nucleus that has just fallen to its ground state by γ -ray emission.

Question 4 (Objective 1)

Decide which of the following statements is a suitable definition of the following terms.

- A Moderator.
- B Nuclear Fusion.
- C Control Rod.
- D Critical Mass.
- E Nuclear Fission.

- 1 The material which reduces the number of free neutrons in a reactor.
- 2 The mass of uranium, or other fissionable material, which is contained in one fuel rod of a nuclear power reactor.
- 3 A rod containing a nuclide with a special affinity for neutrons, which reduces the number of neutrons in a reactor when it is pushed deeper into the core.
- 4 A process in which two heavy nuclei with small total binding energies come together to form an even heavier nucleus with a larger total binding energy.
- 5 A material which is introduced into a reactor to slow down neutrons.
- 6 A carbon rod which is placed in a nuclear reactor to increase the number of free neutrons and encourage fission processes.
- 7 The amount of uranium, or other fissionable material, which, when it is contained in a suitably small volume, will undergo a spontaneous chain reaction.
- 8 The rod of uranium which is pushed further into the reactor when the temperature rises above a safe level.
- 9 A process involving light nuclei which increases the mean binding energy per nucleon.
- 10 That mass of water which, when formed into a freely forming drop, will break spontaneously into two or more smaller drops.
- 11 The block of a special type of boron which forms the fuel of a nuclear reactor.
- 12 A process in which a heavy nucleus, which may have been excited, splits spontaneously into two or more daughter nuclei.

Question 5 (Objective 7)

When a $^{20}_{11}\text{Na}$ nucleus undergoes β -decay, do you expect it to emit an electron or a positron?

Question 6 (Objective 6)

Use the Figures 6 (a) and 6 (b) (pp. 18, 20) in the text to answer the following questions.

- How many stable nuclides have $Z = 14$?
- How many stable nuclides have $A = 50$?
- How many observed nuclides are shown with $N = 132$?
- Is $^{205}_{80}\text{Hg}$ stable?
- Is $^{35}_{16}\text{S}$ stable?
- Is ^7_3Li stable?
- Does $^{28}_{95}\text{Am}$ exist?

Question 7 (Objective 7)

Do you expect nuclides with odd or even numbers of neutrons to make good moderators for chain reactions? Do you expect nuclides with odd or even numbers of neutrons to make good control rod material?

Question 8 (Objective 7)

Using Figure 9 (p. 25) in the text, work out the Z and A values for the nuclide produced in the decay series from U^{238}_{92} after six α -decays and two β^- -decays. What element is this?

Question 9 (Objective 4)

Why are high-energy particles needed to examine the structure and size of a nucleus?

- Because the electrons around the nucleus act as a shield.
- Because the nuclear charge repels charged particles aimed at it.
- Because the incident particles should have a small wavelength.

Question 10 (Objective 5)

Below, there is a list of binding energies for the first nucleon to be removed from a sequence of nuclides beginning at ${}^6_3\text{Li}$. Notice that each successive nuclide is the one which remains after removing the first nucleon from its predecessor. (Check that you understand the significance of a negative binding energy.)

- (a) List in succession the nucleons which have to be removed from each nuclide to reach the next on the list.
- (b) Calculate the mean binding per nucleon.

${}^6_3\text{Li}$	5.17 MeV
${}^5_3\text{Li}$	- 1.47 MeV
${}^4_2\text{He}$	20.5 MeV
${}^3_2\text{He}$	5.44 MeV
${}^2_1\text{H}$	2.18 MeV
${}^1_1\text{H}$	

Question 11 (Objective 9)

Using the list of binding energies for the first nucleon in question 10, calculate the mass defect of ${}^4_2\text{He}$ in a.m.u. (Slide-rule accuracy is sufficient; use Table I (p. 19) in the text for any additional information.)

Question 12 (Objective 10)

There are three statements below about the merits of methods for generating electric power. Which of these statements are basically unfavourable to nuclear power generation by fission, by a fusion technique, or by both, or neither?

- A Major technical problems still remain unsolved.
- B The power stations will cause air pollution.
- C The fuel must be radioactive and therefore dangerous to prepare.
- D The method consumes a natural resource which is in limited supply.
- E The method creates dangerous waste materials.

Self-Assessment Answers and Comments

Question 1

- (a) 10^{-15} m (see the beginning of section 31.2.1).
- (b) Much more (see Figure 2, p. 14).
- (c) 10^{-16} m (this can be deduced from equation 3 (p. 10) with $A=1$).
- (d) A few (see Figure 2).

Question 2

${}^{64}_{30}\text{Zn}$ is the convention for the nucleus with $A=64$; $Z=30$. So using the equation given:

$$\begin{aligned} r &= 1.2 A^{\frac{1}{3}} \\ &= 1.2 (64)^{\frac{1}{3}} = 1.2 \times 4 \\ &= 4.8 \text{ fm.} \end{aligned}$$

From equation 2 in the text,

$$\lambda = 2r \sin \theta / 1.22.$$

In the experiment $\theta = 30^\circ$, so $\sin \theta = 0.5$.

Thus
$$\lambda = \frac{2r \cdot 0.5}{1.22} = \frac{r}{1.22}.$$

However
$$p = \frac{h}{\lambda} = h \times \frac{1.22}{r} = \frac{h \cdot 1.22}{4.8 \times 10^{-15}}$$

so
$$\begin{aligned} p &= \frac{6.6 \times 10^{-34} \cdot 1.22}{4.8 \times 10^{-15}} \\ &= 1.65 \times 10^{-19} \text{ N s} \end{aligned}$$

Question 3

- A Mean binding energy per nucleon: 11
- B Neutron excess: 9
- C Nuclear energy level: 2
- D Excited nucleus: 4.

Question 4

- A: 5
- B: 9
- C: 3
- D: 7
- E: 12.

Question 5

The $^{20}_{11}\text{Na}$ nucleus has $A=20$, $Z=11$, therefore the number of neutrons, N , $=20-11=9$.

So, in this case, $Z > N$.

So you should *expect* a positron to be emitted.

Question 6

(a) $Z=14$ corresponds to Si; 3 stable nuclides with $A=28, 29, 30$.

(b) $A=50$: 3 stable 'isobars' $^{50}_{24}\text{Cr}$; $^{50}_{23}\text{V}$; $^{50}_{22}\text{Ti}$.

(c) 8 observed nuclides have $N=132$ from $^{214}_{82}\text{Pb}$ to $^{221}_{89}\text{Ac}$.

(d) No.

(e) No.

(f) Yes.

(g) No.

Question 7

For a moderator there should be no strong affinity for an extra neutron. Even numbers of neutrons are desirable, as in $^{12}_6\text{C}$. There is one exception. Sometimes ^2_1H is used as a moderator, but this is a special case. Being a light atom it is an excellent moderator. For a control rod there should be an affinity for an extra neutron, so an odd number is preferred, as in $^{10}_5\text{B}$.

Question 8

The end product is $^{214}_{82}\text{Pb}$; lead.

The new values of A and Z are worked out as follows:

$$\begin{aligned} Z(\text{end}) &= Z(\text{start}) - (6 \times 2) + 2 \\ &= 92 - 12 + 2 = 82 \end{aligned}$$

$$\begin{aligned} A(\text{end}) &= A(\text{start}) - (6 \times 4) \\ &= 238 - 24 = 214 \end{aligned}$$

Question 9

C The effect described in section 31.2.1 is a *diffraction* effect, which only takes place if the wavelength of the incident particles is comparable to the size of the nucleus.

Question 10

(a) n; p; n; p; n (n=neutron; p=proton)

(b) Since mean b.e./nucleon = (total b.e.)/(number nucleons)

$$\begin{aligned} \text{Mean b.e./nucleon} &= (\text{sum of energies given})/6 \\ &= 5.30 \text{ MeV/nucleon} \end{aligned}$$

Question 11

The binding energy of the ${}^4_2\text{He}$ nucleus is the sum of all the energies in question 10 up to ${}^4_2\text{He}$,

$$\begin{aligned}\text{i.e. b.e. of } {}^4_2\text{He} &= 2.18 + 5.44 + 20.5 \text{ MeV} \\ &= 28.12 \text{ MeV}\end{aligned}$$

But binding energy (MeV) = mass defect (MeV/ c^2)

From Table I the ratio of a.m.u. to MeV/ c^2 can be deduced, for example using the ${}^{12}_6\text{C}$ nucleus:

$$\text{Mass in a.m.u.} = \text{Mass in MeV}/c^2 \times \frac{12}{11178}$$

$$\begin{aligned}\text{mass defect } {}^4_2\text{He} &= 28.12 \text{ MeV}/c^2 \\ &= 28.12 \times \frac{12}{11178} \text{ a.m.u.} \\ &\approx 3.0 \times 10^{-2} \text{ a.m.u.}\end{aligned}$$

Question 12

- A fusion.
- B neither (but conventional methods using fossil fuels do).
- C fission (possible fusion processes are thought of as starting from non-radioactive materials).
- D fission (and fossil fuel methods; fusion processes are most likely to only need water!).
- E fission.

Acknowledgements

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Nuclear Power Group for Fig. 12.

